Determining sustainable lignocellulosic bioenergy systems in the Cape Winelands District Municipality, South Africa

by
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DECLARATION

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ABSTRACT

The energy paradigm shift from fossil fuels to renewable energy sources is driven, among others, by a growing sustainability awareness, necessitating more sophisticated measurements in terms of a wider range of criteria. Technical efficiency, financial profitability, environmental friendliness and social acceptance are some of the factors determining the sustainability of renewable energy systems. The resulting complexity and conflicting decision criteria, however, constitute major barriers to processing the information and decision-making based on the information. Seeking to implement local bioenergy systems, policymakers of the Cape Winelands District Municipality (CWDM), South Africa, are confronted with such a problem.

Following a case study approach, this study illustrates how life-cycle assessment (LCA), multi-period budgeting (MPB) and geographic information systems (GIS) can aid the decision-making process by providing financial-economic, socio-economic and environmental friendliness performance data in a structured and transparent manner, allowing for a comparison of the magnitude of each considered criterion along the life-cycle. However, as the environmental impacts cannot readily be expressed in monetary terms on a cardinal scale, these considerations are given less attention or are omitted completely in a market economy. By measuring the various considerations on an ordinal scale and by attaching weights to them using the multi-criteria decision analysis (MCDA) approach, this study, illustrates how to internalise externalities as typical market failures, aiding policymakers of the CWDM to choose the most sustainable bioenergy system.

Following the LCA approach, 37 lignocellulosic bioenergy systems, encompassing different combinations of type of harvesting and primary transport, type of pretreatment (comminution, drying, and fast pyrolysis) and location thereof (roadside or landing of the central conversion plant), type of secondary transport from the roadside to the central conversion plant, and type of biomass upgrading and conversion into electricity, were assessed against five financial-economic viability criteria, three socio-economic potential criteria and five environmental impact criteria. The quantitative performance data were then, as part of the MCDA process, translated into a standardised 'common language' of relative performance. An expert group attached weights to the considered criteria using the analytical hierarchy process (AHP). The 'financial-economic viability' main criterion received a weight of almost 60%, 'socio-economic potential', nearly 25% and 'lowest environmental impact', the remainder of around 16%. Taking the prerequisite of financial-economic viability into consideration, the preferred option across all areas of the CWDM (despite various levels of productivity) comprises a feller-buncher for harvesting, a forwarder for primary

transportation, mobile comminution at the roadside, secondary transport in truck-container-trailer combinations and an integrated gasification system for the conversion into electricity.

OPSOMMING

Die energie paradigma verandering van fossielbrandstowwe na hernubare energiebronne word gedryf deur ‘n groeiende klem op volhoubaarheid, wat ook meer gesofistikeerde meting in terme van ‘n wyer verskeidenheid maatstawwe vereis. Tegniese doeltreffendheid, finansiële winsgewendheid, omgewingsvriendelikheid en sosiale aanvaarbaarheid is sommige van die faktore wat die volhoubaarheid van hernubare energie stelsels bepaal. Die verskeidenheid oorwegings bring egter kompleksiteit en konflik mee by die verwerking van inligting en die besluitneming wat daarop berus. Beleidmakers van die Kaapse Wynland Distriksmunisipaliteit wat ten doel het om plaaslik bio-energie stelsels te implementeer, word met hierdie probleem gekonfronteer.

Hierdie ondersoek illustreer aan die hand van ‘n gevallestudie benadering hoe lewensiklus analise, multiperiode begroting en geografiese inligtingstelsels besluitneming kan ondersteun deur die voorsiening van finansieel-ekonomiese, sosio-ekonomiese (indiensneming) en omgewingsvriendelikheid prestasie data op ‘n gestruktureerde en deursigtige wyse. Dit maak die vergelyking van die waardes van al die kriteria by elke fase van die lewensiklus moontlik. Aangesien die omgewingseffekte nie geredelik in monetêre terme op ‘n kardinale skaal gemeet kan word nie, kry hulle binne die markekonomie minder aandag of word selfs buite rekening gelaat. Deur hierdie verskeidenheid kriteria op ‘n ordinale skaal te meet en gewigte met behulp van multikriteria besluitneming aan hulle toe te ken, toon hierdie ondersoek hoe om eksternaliteite as tipiese markmislukkings te internaliseer om beleidmakers van die Kaapse Wynland Distriksmunisipaliteit in staat te stel om die mees volhoubare bio-energie stelsel te kies.

Met behulp van lewensiklus analise is 37 lignosellulose bio-energie stelsels geïdentifiseer as verskillende kombinasies van oes van die bome, primêre vervoer van houtstompe, vooraf verwerking (verspaandering, droging, vinnige pirolise), die ligging van hierdie aktiwiteite (langs ‘n plantasie of by ‘n sentrale omsettingsaanleg), tipe sekondêre vervoer van houtspaanders vanaf die plantasie na die sentrale omsettingsaanleg en tipe biomassa opgradering en omsetting van die houtspaanders na elektrisiteit. Die verskillende stelsels is gemeet aan die hand van vyf finansieel-ekonomiese kriteria, drie indiensneming potensiaal kriteria en vyf omgewingsimpak kriteria. Die kwantitatiewe metings is deur middel van multikriteria besluitneming omgeskakel na ’n gestandaardiseerde “gemeenskaplike taal” van relatiewe prestasie. Lede van ‘n ekspertgroep het gewigte is aan die onderskeie kriteria met behulp van die analitiese hierargie proses toegeken. Aan die finansieel-ekonomiese lewensvatbaarheid hoof kriterium is ‘n gewig van by die 60% toegeken, aan die indiensnemingspotensiaal bykans 25% en aan omgewingsvriendelikheid sowat 16%. Die voorkeur kombinasie vir al die areas van die Kaapse Wynland Distriksmunisipaliteit sluit in ‘n

saag-bondelaar vir die oesproses, ‘n plantasie-vragmotor vir primêre vervoer, mobiele verspaandering langs die plantasie, ‘n vragmotor-skeepshouer-treiler kombinasies vir die sekondêre vervoer van houtspaanders en ‘n geïntegreerde vergassingstelsel vir die omsetting van houtspaanders na elektrisiteit.

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[1] Any opinion, findings and conclusions or recommendations expressed in this dissertation are those of the author and the South African National Research Foundation does not accept any liability in regard thereto.

*After all, sustainability means running the global environment - Earth Inc. - like a corporation: with depreciation, amortization and maintenance accounts. In other words, keeping the asset whole, rather than undermining your natural capital.**

*Maurice Strong, Canadian entrepreneur and former under-secretary general of the United Nations

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LIST OF ABBREVIATIONS AND ACRONYMNS

AP	Acidification Potential
BCS	Bioenergy Conversion System
BII	Biodiversity Intactness Index
BPA	Biomass procurement area
CBA	Cost-Benefit Analysis
CLM	Centrum voor Milieuwetenschappen Leiden
	(Institute of Environmental Sciences, University of Leiden)
CS	Cropping System
CWDM	Cape Winelands District Municipality
DECP	Direct Employment Creation Potential
dLUC	Direct Land Use Change
EHV	Effective heating value
EP	Eutrophication Potential
FU	Functional Unit
GaBi 4	Life Cycle Assessment software (“Ganzheitliche Bilanzierung“)
GHG	Greenhouse Gases
GWP	Global Warming Potential
HHV	Higher heating value
HV	Heating value
IPCC	Intergovernmental Panel of Climate Change
ISO	International Organisation of Standardisation
LBS	Lignocellulosic bioenergy system
LCA	Life Cycle Analysis/Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LUC	Land Use Change
MC	Moisture content
MCDA	Multi-Criteria Decision Making Analysis
MPB	Multi-Period Budgeting
NREC	Non-Renewable Energy Consumption
NRR	Non-Renewable Resources

OCE	Overall Conversion Efficiency
ODP	Ozone Depletion Potential
PM	Particle Matter
POCP	Photochemical Ozone Creation Potential
SANERI	South Africa's National Energy Research Institute
SRC	Short Rotation Coppice system
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compounds
WF	Water Footprint
WSSD	World Summit on Sustainable Development

LIST OF UNITS

°C	Temperature in Celsius
kW	Kilowatt
MW	Megawatt
GW	Gigawatt
MJ	Megajoule
GJ	Gigajoule

LIST OF ELEMENTS AND CHEMICAL FORMULAS

C	Carbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H	Hydrogen
HCl	Hydrogen chloride
K	Potassium
N	Nitrogen
N_2O	Di-nitrogen Monoxide (Laughing gas)
N_{min}	Mineralised nitrogen
N_{org}	Organic fixed nitrogen
NH_3^-	Ammonia
NH_4^+	Ammonium
$NMVOC$	Non Methane Volatile Organic Compounds
NO	Nitrogen Oxide
NO_x	Nitrous gases
NO_3^-	Nitrate
O	Oxygen
P	Phosphor
PO_4^{3-}	Phosphate
SO_2	Sulphur dioxide

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1 CHAPTER: INTRODUCTION AND ORIENTATION

1.1 Introduction and background

Worldwide about 2.6 billion people live on less than two dollars per day, while the current ecological footprint of global consumption and production patterns exceeds the earth's capacity to regenerate (UNEP, 2010). With current energy policies and management this situation is unlikely to improve, since the world's energy consumption is projected to more than triple between 1990 (164 exajoules, EJ) and 2035 (508 EJ) (U.S. IEA, 2011). This demand, however, cannot be satisfied by conventional energy sources such as crude oil, natural gas, coal and nuclear power combined (Lange, 2007). Finite reserves and a rapidly increasing demand for oil will inevitably force world economies to abandon oil as the primary source of energy (Laird, 2008). Another force compelling world economies to reconsider current energy policies and management is the inability of the environment to maintain its sink function, i.e. the ability to maintain its assimilating capacity without the unacceptable degradation of its future waste absorbing capacity or other important services (Goodland, 1995). There is growing scientific consensus that climate change is driven by anthropogenic emissions of greenhouse gases to the atmosphere and that the use of fossil fuels for energy is the dominant source of these emissions (IPCC, 2007).

This has resulted in an entirely new energy paradigm ranging from fossil to renewable energy sources, particularly in the developed world, where the development of hydro, solar, wind and biomass-based energy systems is receiving great attention, with the aim of extending current energy mixes and replacing conventional energy systems. While significant progress can be seen in many European and North American countries, the implementation of renewable energies is still at an early stage of development on the African continent. South Africa relies on fossil fuels such as coal and oil to generate more than 90 percent of its electricity (ESKOM, 2010). While projections based on known reserves indicate sufficient coal for 114 years, pollution of the air, water and soil is causing serious environmental damage. Additionally, an outdated electricity infrastructure and low capacities of electricity generated have resulted in scheduled power cuts by the monopolistically acting national energy supplier, ESKOM, which has had a severe impact on South Africa's economic growth. A first serious step towards introducing renewable energies was taken in 2010, when the South African government initiated a renewable energy programme aimed at procuring 3 725 Megawatt (MW) of electricity between 2014 and 2016 mainly from biomass, wind, solar energy, and small-scale hydro energy, with additional plans aimed at procuring 17 800 MW from these sources by 2030.

Against this background, biomass is considered to be one of the most promising alternatives to conventional fuels and feedstocks, as it is the only renewable source of fixed carbon that can be converted to liquid, solid and gaseous fuels as well as to heat and power (Amutio et al., 2011). Moreover, biomass is considered 'carbon neutral' over its life cycle because the combustion of biomass releases the same amount of CO_2 as was captured during its growth. By contrast, fossil fuels release CO_2 that has been locked up for millions of years. Furthermore, biomass is considered the renewable energy source with the highest potential to contribute to the energy needs of modern society for both developed and developing economies world-wide (IEA, 2000, Bridgwater, 2002). Bioenergy has an almost closed CO_2 cycle, but there are greenhouse gas emissions (GHG) in its life cycle, largely resulting from the production stages: external fossil fuel inputs are required to produce and harvest the feedstocks, in processing and handling the biomass, in operating bioenergy plants and in transporting the feedstocks and biofuels (Cherubini et al., 2009). In recent years, short-rotation woody crops such as willow, poplar and eucalyptus have turned out to be the biomass materials with the highest energy potential (Guerrero et al., 2005).

The need for security and diversification of energy supplies as well as for less reliance on fossil fuels, the uncertainty surrounding oil prices, and increasing concerns over environmental degradation and climate change effects are some of the major social, political, and economic challenges that have prompted the international community to work harder at promoting renewable energy sources (Perimenis et al., 2011: 1782). However, this new energy paradigm has also demanded new ways of measuring the viability of energy sources. While in the past, the 'success' of energy carriers was mostly driven by financial considerations, leading to fossil fuels such as coal and oil being the preferred choices, the introduction of renewable energies has resulted in more of a sustainability driven approach, necessitating more sophisticated measurements of a wider range of criteria. The financial-economic competitiveness still plays an important role, but medium- and long-term aspects need to be taken into account, especially when considering the growing scarcity of fossil energy carriers. A major feature of any renewable energy product is also the degree to which it can reduce environmental impacts, e.g. carbon dioxide (CO_2) emissions, associated with the use of the fossil energy that it will replace. Another important feature is the extent to which renewable energies can contribute to socio-economic potential. Bioenergy particularly is considered a local energy source, as it requires large areas to ensure a sufficient and sustainable supply, resulting not only in a change of agricultural and forestry production patterns but also in significant employment creation, particularly in rural areas. In contrast, generating fossil-fuel-driven energy is considered a large-scale, capital-intensive operation that is limited to relatively small areas, resulting not only in significant environmental impacts locally (e.g. acidification, eutrophication, human health) and globally (e.g. climate change), but also in other social challenges such as limited employment creation, migration to cities, and infrastructure and food constraints.

The main goal of this study is to provide a blue print for identifying the most sustainable bioenergy system in a decision-making context, taking financial-economic viability, environmental impact and socio-economic potential criteria into consideration.

1.2 Problem statement

Cost-benefit analysis (CBA) is a monetary assessment method that is traditionally used to test the financial viability of energy projects. However, the growing scarcity of fossil energy, energy security, and public and political sensitivities to environmental issues have led not only to promoting indigenous, renewable energy sources, but also to prompting the scientific community to develop assessment methods other than monetary ones, aimed at determining the environmental or socio-economic performance of alternative energy systems.

A variety of studies concur that environmental, financial, and socio-economic criteria need to be considered when seeking the most sustainable alternative. However, most of them fall short in their application, as they either consider only a single dimension (finance, social or environment) or take only a very limited number of other aspects into account (e.g. only one for each dimension). This narrow measurement of ‘success’ may not lead to the implementation of the most sustainable alternative. The sustainability of production is, however, essential, particularly in the context of bioenergy projects, which depend on the support of many stakeholders with different perspectives; ‘sustainability of production’ refers to the implementation of pathways that are technically efficient, economically affordable, environmentally sound, and socially acceptable (Perimenis et al., 2011). The resulting complexity, however, constitutes a major barrier to the implementation of renewable projects, as much information of a complex and conflicting nature, often reflecting different viewpoints and often changing with time, needs to be processed.

The Cape Winelands District Municipality (CWDM) in the Western Cape, South Africa, is confronted with such a decision-making problem. The insecurities in the power supply by ESKOM have prompted public decision makers of the CWDM to investigate the possibility of implementing local renewable bioenergy systems aimed at improving energy security and reducing the dependency on ESKOM, while maximising all the dimensions of sustainability. The promotion of more sustainable bioenergy systems thus called for an approach that identifies and evaluates potential bioenergy alternatives in terms of a wider variety of criteria.

1.3 Research goal and objectives

Aimed at supporting decision-making, this study applies life-cycle assessment (LCA) as well as complementary tools such as geographic information systems (GIS) and multi-period budgeting (MPB) to provide financial-economic, socio-economic and environmental performance data. Multi-criteria decision analysis (MCDA) is used to integrate and evaluate the provided performance data, to determine the most viable lignocellulosic bioenergy system in the CWDM.

1.4 Research approach and methodologies

The life-cycle assessment (LCA) approach, originally developed as an environmental assessment tool, has gained recognition as a tool that can provide environmental performance information to support decision-making in both the private and public sectors (Basson and Petrie, 2007). There is broad agreement in the scientific community that LCA is one of the best methods for evaluating the environmental burdens associated with biofuel and bioenergy production, as it identifies energy and materials used as well as waste and emissions released to the environment; moreover, it allows the identification of opportunities for environmental improvement (Cherubini et al., 2009).

Due to its structured and systematic approach, LCA appears to be well suited to being integrated with other, complementary assessment methods such as multi-period budgeting (MPB) and geographic information systems (GIS). Widely accepted and applied, these methods could assist in covering the technical, financial-economic and socio-economic aspects along a product's life-cycle. However, while LCA and other complementary methods may be suitable methods for providing environmental, financial and socio-economic performance data, the main problem in finding the most viable/sustainable alternative in a decision environment with multiple and often conflicting objectives persists (Azapagic and Clift, 1999).

To overcome this problem, an additional method is required to support decision-making that organises and synthesises the respective information, that is capable of integrating mixed sets of data (qualitative and quantitative), and that assists the decision maker to place the problem in context and to determine the preferences of the stakeholders involved. Multi-criteria decision analysis (MCDA) is an assessment tool aimed at aiding such a decision-making process. Based on a number of defined criteria, the goal of a decision maker is to identify an alternative solution that optimises all the criteria (Peremenis et al., 2011: 1784). However, in complex projects like bioenergy assessments, it is impossible to optimise all the criteria at the same time; therefore, a compromise solution needs to be actively sought by using subjective judgements of the considered criteria and by combining these as weighted scores to obtain an overall ranking of alternatives. Thus, MCDA could aid decision-making processes by integrating objective measurement with value judgement, by making subjectivity explicit, and by managing this subjectivity in a transparent and reproducible manner.

1.5 Statement of hypothesis

The following hypotheses are put forward for this research:

- **Hypothesis I:**
  Life-cycle assessment (LCA) and other complementary system assessment methods including multi-period budgeting (MPB) and geographic information systems (GIS) can be used as a structured and comprehensive technique for the detailed analysis of complex lignocellulosic bioenergy systems to provide quantitative financial-economic, socio-economic and environmental performance data.
- **Hypothesis II:**
  Multi-criteria decision analysis (MCDA) can aid the decision-making process to determine the most sustainable lignocellulosic bioenergy system for the CWDM by integrating and evaluating the provided performance data.

1.6 Chapter layout

This dissertation is presented in eight chapters, a list of references and 76 annexures. Chapter 1 serves as a general introduction and orientation of the research problem. Chapter 2 entails a description of the study area, and a description and definition of the bioenergy feedstock properties applicable to the study area. Chapter 3 provides the theoretical foundation of the assessment methodologies applied, as well as a summary of a variety of recent LCA and MCDA studies in the fields of agriculture, forestry and bioenergy. The combined use of both methods found in the literature is also discussed.

Following the LCA approach, Chapter 4 comprises the goal and scope definition. It includes the definition of the functional unit, the technical system boundaries, geographical and time boundaries, as well as the boundaries in relation to the natural system. Chapter 5 provides the life-cycle inventory (LCI), where information is gathered on all process-related inputs and outputs in the studied system. Aimed at understanding the significance of the LCI results, Chapter 6 entails the life-cycle impact assessment (LCIA), where the environmental loads from the inventory results are translated into environmental impacts, which include, *inter alia*, global warming potential, acidification potential, and other categories typically not included in LCAs such as internal rate of return and direct employment creation potential.

Chapter 7 presents an application of the analytical hierarchy process (AHP), one of the commonly applied multi-criteria decision analyses (MCDA). With the aim of supporting decision-making, the performance data generated in the previous chapter was translated into a common language and weighted and integrated into a single indicator, by a weighting process, resulting in a ranking of the alternatives assessed. The last chapter encompasses the conclusions, summary and recommendations for future research.

2 CHAPTER: STUDY AREA AND RESOURCE BASELINE

2.1 Introduction

In the following, Chapter 2 gives background information on the study area, the Cape Winelands District Municipality (CWDM), such as geographical location and extent, related unemployment figures, and climate variables (e.g. rainfall, temperature). Moreover, Chapter 2 discusses the resource baseline in terms of the availability of lignocellulosic biomass grown in short-rotation coppice (SRC) systems, based on a land and biomass availability assessment. Geographic information systems (GIS) were used to determine the extent and location of potential production sites, based on land quality considerations (e.g. soil and climate characteristics) and on avoiding biodiversity hotspots as well as urban developments, among others. This is followed by a description, definition and classification of the biomass, as well as of key feedstock parameters relevant for the generation of electrical and thermal energy.

2.2 The Cape Winelands District Municipality

The Cape Winelands District Municipality (CWDM), with a total area of 22 300km^2 (2.23 million ha), is one of five district municipalities in the Western Cape, South Africa.

The total population of the CWDM is 679 210, with a labour force of 290 113. Of this, 230 196 people are employed (Daniels, 2011), with 202 782 workers in the formal sector and 27 414 workers in the informal sector. The official unemployment rate was estimated at 20.7% in 2010. Table 1, below, shows more detailed data for the respective municipalities within the CWDM.

Table 1: Unemployment in the CWDM

		Municipalities in CWDM				
	Cape Winelands	**Stellen-Bosch**	**Draken-stein**	**Brëede Valley**	**Witzen-berg**	**Lange-berg**
Unemployment (official)	60 126	10 216	20 109	15 237	5 564	8 946
Unemployment rate (%)	20.7%	19.1%	23.2%	22.6%	13.3%	23.9%
Formal employment	202 782	46 953	52 547	45 484	34 283	22 593
Informal employment	27 414	5 716	6 690	6 118	4 367	4 523
Total [a]	**290 113**	**53 462**	**86 632**	**67 412**	**41 821**	**37 473**

Source: Daniels (2011)

Note:
[a] Excluding district municipality area statistics.

The CWDM is characterised by a Mediterranean climate and a historically strong deterministic water supply (winter rainfall) from April to August. The average mean annual precipitation (MAP) is 470mm for the CWDM, with a high geographic variation and a minimum MAP as low as 72mm for some areas (in the north-eastern parts of the CDWM); the maximum MAP reaches as high as 3 198mm in the south-western part of the CWDM. As Figure 1, below, shows, most parts of the CWDM experience even less than the South African MAP average of 450mm per year and, therefore, are prone to seasonal droughts.

During the peak of summer, in February, the average maximum temperatures reach up to 45°C degrees, while in July, when winter is peaking, some areas towards the interior of the CWDM reach average minimum temperatures of minus 11°C (with an overall average of minus 2°C). The south-western part of the CWDM is mainly frost free, but some valleys experience up to 27 days of frost per year. For more details on the climate conditions of the CWDM, see Von Doderer (2009: 15-16, 70-72).

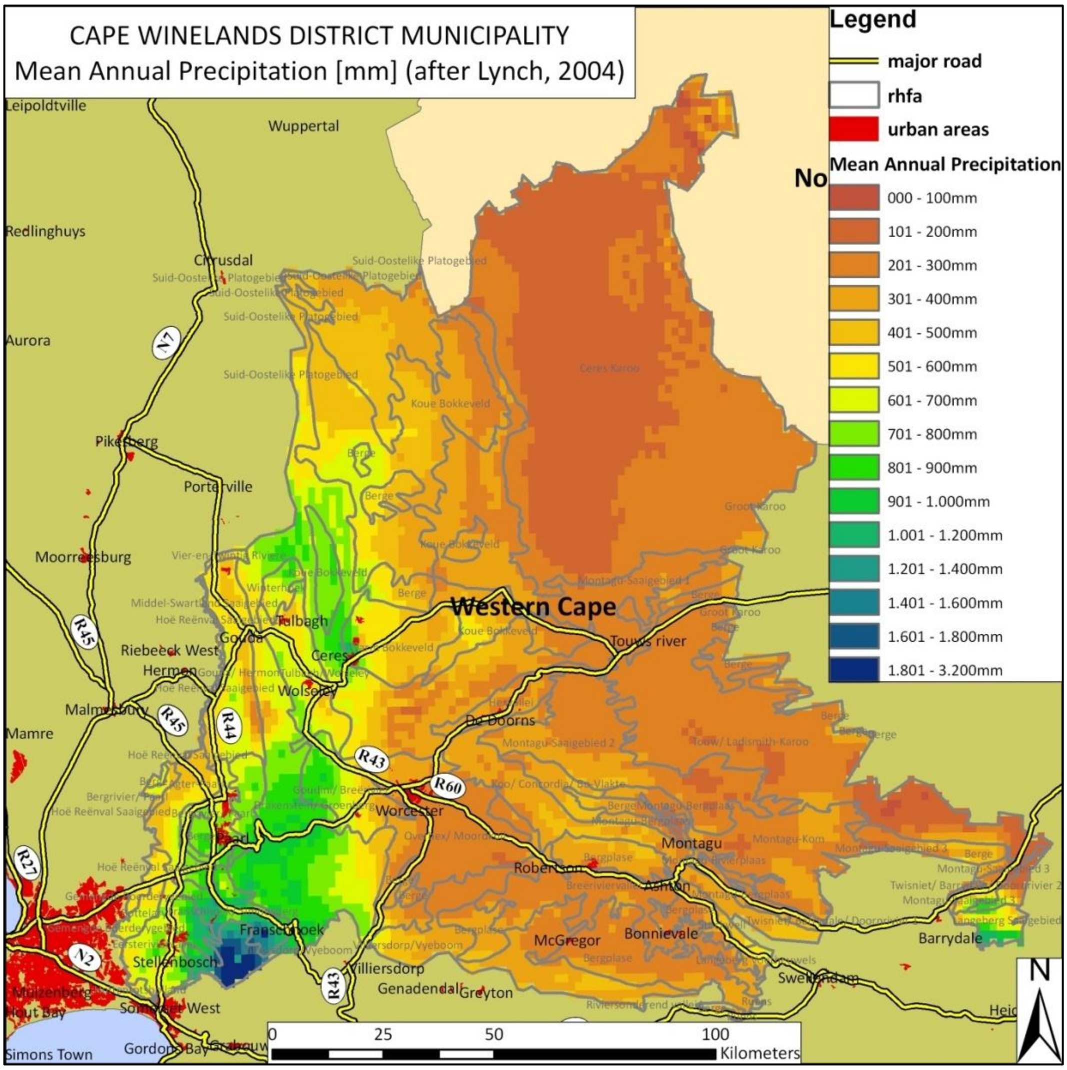

Figure 1: Mean annual precipitation of the CWDM

Notes:
rhfa relative homogenous farming area
Source: Schulze et al. (2006)

2.3 Study area: biomass resource baseline

The study area was assessed using geographic information systems (GIS) in order to determine the land availability and the potential productivity of available land for producing biomass in short-rotation coppice (SRC) systems (Von Doderer, 2009). Non-suitable areas, such as urban areas, areas with terrain limitations (i.e. areas that are too steep: > 35%), areas with water limitations (aridity index) and ecologically sensitive areas (e.g. protected areas, critical biodiversity areas, and water catchment areas), have been excluded, resulting in about 175 000 hectares (ha) that could be used for producing energy wood in SRC systems. Table 2 shows the available biomass production areas in the CWDM in terms of land use types and slope classes.

Table 2: Available biomass production areas in CWDM

Land use type	Slope classes				Total ≤ 35%	
	≤ 10%	11-20%	21-30%	31-35%	ha	%
Intensive permanent and temporary farmland (ha)	3 028	328	34	4	3 394	2%
Extensive dryland and improved grassland (ha)	53 842	5 329	631	121	59 923	34%
Forest plantations (ha)	0	0	0	0	0	0%
Fynbos, shrubland and bushland (ha)	51 147	31 320	21 125	8 818	112 410	64%
Total (ha)	108 017	36 976	21 790	8 943	175 726	100%
Total (%)	62%	21%	12%	5%	100%	

Source: *Von Doderer (2009)*

Various developments in the South African forestry industry in recent years – such as strong and continued growth of demand for wood and wood products, termination of timber production at some state plantations due to low productivity, particularly in the Southern and Western Cape (VECON-Consortium, 2006), as well as the increased use of logging residues by the existing forestry industry for generating its own energy – has led to forest plantation residues in the CWDM not being available for generating bioenergy.

The use of invasive alien plant (IAP) species, such as Black Wattle (*Acacia mearnsii*) and Port Jackson (*Acacia saligna*), can also be ruled out, as they are distributed over wide areas and, in many cases, in difficult terrain, resulting in high procurement costs. Furthermore, woody biomass sourced from invaded areas, after having been harvested, would not comprise a sustainable supply of biomass for generating electricity. IAPs pose a direct threat to South Africa's biological diversity, to water security, the ecological functioning of natural systems, and the productive use of land. Hence, the clearance of invaded areas of IAPs without their re-establishment is desired.

The biomass productivity assessment indicates that about 1.4 million tons of fresh lignocellulosic biomass could be supplied annually, assuming medium productivity (Von Doderer, 2009). Eighteen tree species were identified as being suitable for the area and climate conditions, of which four are indigenous and 14 are exotic (see Table 3, below). Indigenous species (e.g. *Acacia karoo*) are expected to produce higher yields in the interior, low production potential areas in the north-east of the CWDM, whereas exotic species (e.g. *Eucalyptus cladocalyx*) grow better in areas with higher production potential, compared with indigenous species.

Table 3: Suitable indigenous and exotic tree species for biomass production in the CWDM

Genera	**Species**	**Common name**	**Origin[a]**	**Re-generation**		**Ease of cultivation[c]**	**Invasiveness[d]**	**Adaptability to site conditions**
				technique	**coppicing**			
Acacia	*karoo*	Sweet Thorn	ind.	se	No	-	1	5
	mearnsii	Black Wattle	ex.	se	No	-	5	5
	saligna	Port Jackson	ex.	se	Yes	1	4	5
Casuarina	*cunninghamiana*	Beefwood	ex.	se	-	1	3	5
	glauca	Swamp She-Oak	ex.	se	-	1	3	5
Eucalyptus	*albens*	White Box	ex.	se	Yes	1	3	3
	camaldulensis	Red River Gum	ex.	se	Yes	1	3	5
	cladocalyx	Sugar Gum	ex.	se	Yes	1	3	5
	globulus	Blue Gum	ex.	se	Yes	1	3	5
	gomphocephala	Tuart	ex.	se	Yes	1	3	3
	melliodora	Honey-scented Gum	ex.	se	Yes	2	3	3
	polyanthemos	Red Box	ex.	se	Yes	1	3	5
Pinus	*halepensis*	Aleppo Pine	ex.	se	No	2	4	3
	radiate	Monterey Pine	ex.	se	No	1	3	5
Rhus	*Lancea*	Karree	ind.	se/cu	Yes	1	0	5
	pendulina	White Karree	ind.	se/cu	Yes	1	0	5
Schinus	*Molle*	Pepper tree	ex.	se	Yes	4	4	2
Ziziphus	*mucronata*	Buffalo Thorn	ind.	se/cu	Yes	4	4	2

Source: Von Doderer (2009)

Notes:

[a] ind. = indigenous; ex. = exotic.
[b] se = seedling; cu = cutting.
[c] Ease of cultivation
(1 – easy, 2 – easy-medium, 3 – medium, 4 – medium-difficult, 5 – difficult).
[d] Invasiveness
(0 – none, 1 – low, 2 – low-medium, 3 – medium, 4 – medium-high, 5 – high).
[e] Adaptability to site conditions
(0 – none, 1 – low, 2 – low-medium, 3 – medium, 4 – medium-high, 5 – high).

Eucalyptus cladocalyx is classified as a category two invasive species and could be commercially utilised in demarcated areas (RSA, 1983). Since it is only a potential transformer of the environment and is not quite as aggressively widespread as *Acacia cyclops*, it would constitute a viable wood species to be planted specifically as fuel wood (Munalula and Meincken, 2009). Current research on other fast-growing species and hybrids at the Department of Forest Science at Stellenbosch University might lead to the introduction of other species of trees for growing in SRC plantations.

Figure 2, below, is showing the availability of potential sites for producing woody biomass in the CWDM. It also shows potential sites for bioenergy conversion, based on access to infrastructure such as main electricity lines, electricity substations, road networks, and potential consumers of by-products (e.g. thermal energy) from the bioenergy conversion.

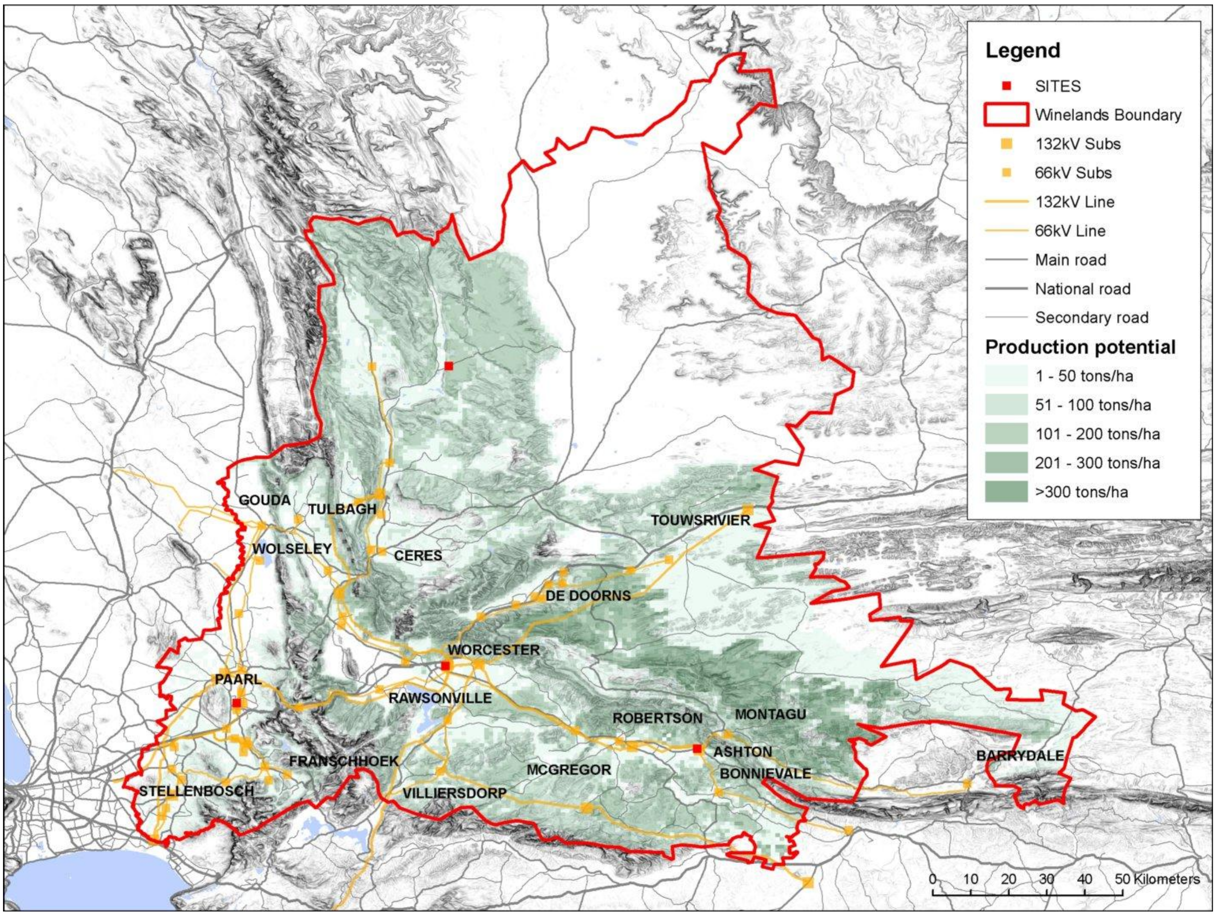

Figure 2: Lignocellulosic biomass availability of the CWDM, including main electricity grid and electricity substations, as well as potential sites for bioenergy conversion

Source: Van Niekerk and Von Doderer (2009)

Fourteen potential bioenergy conversion sites, also referred to as demand points, were identified in the CWDM (Roberts, 2009: 57) (see Table 4, below). The demand points were identified using the following determinants: proximity to substations and major grid lines, in order to minimise feed-in costs; proximity to external customers (e.g. canning industries, distilleries, cheese factories and food processing factories), to whom potential excess heat could be sold, resulting in the improved profitability of combustion and gasification plants; and electricity demand for each town within the CWDM. Furthermore, the proximity of the demand points to the road network was an important consideration, as the accessibility of the demand points affects feedstock transport efficiency and obviates the costs of additional infrastructure.

Table 4: Potential demand points for bioenergy generation in the CWDM

No.	Potential sites	Situated in industrial areas	Close to electricity grid and electricity substations
1	Paarl	a	b
2	Franschhoek	a	b
3	Wolseley	a	b
4	Ceres	a	b
5	Rural Koue Bokkeveld		b
6	Rural Cederberg		
7	Worcester	a	b
8	De Doorns	a	b
9	Robertson	a	b
10	Touwsrivier	a	b
11	Ashton	a	b
12	Bonnievale	a	b
13	Montagu	a	b
14	Rural Montagu		

Notes:

[a] Possibility of selling thermal energy to external customers.

[b] Lower cost of transmitting electricity; if not close to substations, it would be necessary to build new substations or lay new transmission cables.

2.4 Biomass definition and properties

Biomass refers to all organic materials that stem from green plants as a result of photosynthesis. It is a stored source of solar energy in the form of chemical energy, which can be released when the chemical bonds between adjacent oxygen, carbon, and hydrogen molecules are broken by various biological and thermo-chemical processes. Fossil fuels, including primarily coal, oil and natural gas, also originated from 'ancient' biomass that has been transformed through microbial anaerobic degradation and metamorphic geological changes over millions of years (Zhang et al., 2010; McKendry, 2002a; Kandiyoti et al., 2006).

Fossil fuels are considered to be non-renewable sources of energy, considering the rate of their formation (millions of years) and consumption. In addition, burning fossil fuels releases net carbon dioxide (CO_2) to the atmosphere. By contrast, biomass is a renewable resource and is considered to be CO_2 neutral, as the CO_2 released during combustion or other conversion processes is recaptured by the regrowth of the biomass through photosynthesis. In addition, the lower emission of environmentally detrimental gases, such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x), during the combustion of biomass also plays a positive role in reducing global acid rain formation (Jenkins et al., 1998; Ni et al., 2006; IEA, 2007; Zhang et al., 2010).

2.4.1 Biomass classification

Two classification approaches have been proposed based on the origin of the biomass and its properties (Williams, 1992; Jenkins et al., 1998). Based on origin, biomass can generally be divided into four primary classes:

1. Primary residues: by-products of food crops and forest products (for example, wood, straw, cereals, or maize);
2. Secondary residues: by-products of biomass processing for the production of food products or biomass materials (e.g. saw and paper mills, food and beverage industries, or apricot seed);
3. Tertiary residues: by-products of used biomass-derived commodities (e.g. waste, or demolition wood);
4. Energy crops.

Based on properties, biomass can be classified into the following categories:

1. Wood and woody fuel (e.g. hard wood, soft wood, or demolition wood);
2. Herbaceous fuels (for example straw, grasses or stalks);
3. Waste (sewage sludge, refuse-derived fuel);
4. Derivatives (waste from paper and food industries);
5. Aquatic biomass (algae);
6. Energy crops (specifically cultivated for energy purposes).

2.4.2 Biomass composition

Biomass includes a wide range of organic materials, which are generally composed of cellulose, hemicellulose, lignin, lipids, proteins, simple sugars and starches. Among those compounds, cellulose, hemicellulose, and lignin are the three main constituents (Mohan et al., 2006b, Zhang et al., 2010). Biomass also contains inorganic constituents and a fraction of water (Zhang et al., 2010, Jenkins et al., 1998). As for the elementary composition, carbon and oxygen with around 50% and 45% respectively account for more than 90% of the dry weight of a typical biomass. In addition, there are trace amounts of hydrogen (5wt.%), nitrogen (0.9wt.%), and chlorine (0.01-2wt.%).

Since this study deals with bioenergy systems using woody biomass grown in a short-rotation coppice system as a feedstock (i.e. energy crop), greater attention will be given to the different components and the composition of trees suitable for this type of production system.

A complete tree in its appearance can be distinguished between the part above the stump, which in forestry terms is also called whole tree, and the stump-root system. The whole tree, sometimes also called full tree, can be further divided in stem, crown branches and foliage, and in bioenergy terms can be summarised in above-ground biomass. The below-ground biomass includes the root system. Although the stump is not below-ground, it is often counted as below-ground biomass, as it is normally not used commercially and, hence, remains on site.

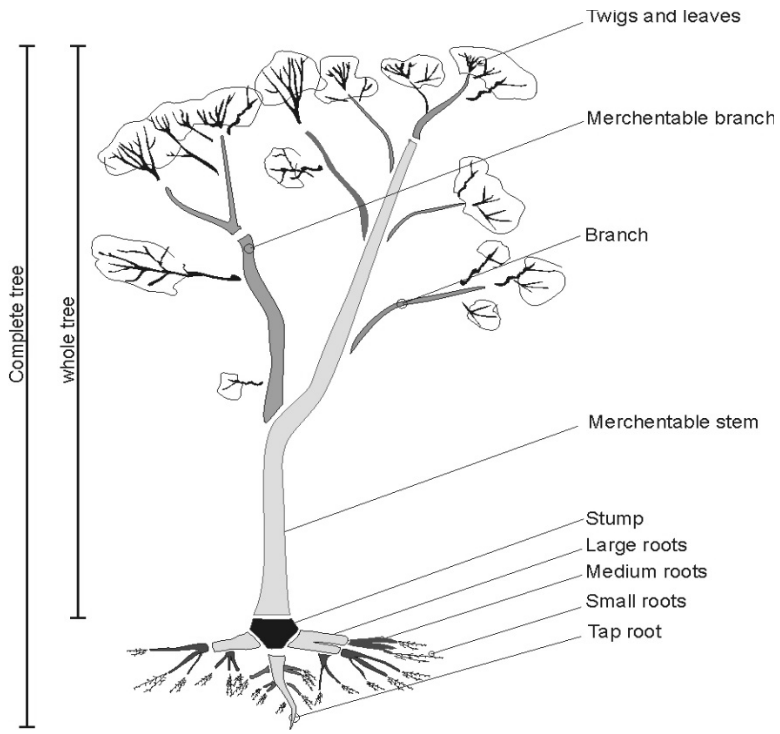

Figure 3: Phenotype and basic components of broad-leaved tree

Source: Seifert (2012)

Based on the approach found in Dovey (2009), three tree components are used for bioenergy, namely, the stemwood, bark and branch biomass (sum of live and dead branch biomass, including all branches and tree tops, i.e. the portion of the stem with an over-bark diameter of less than 7cm).

Dovey's study (2009) shows that whole-tree harvesting, including the bark and branches, increases the biomass by around a half to one third, while exportation of the nutrients is increased by two to four times. Under some management practices, whole-tree harvesting may include the removal of foliage. Although foliage was not included in the study by Dovey, it accounted for 0.5-0.7% of the total above-ground biomass and 5-10% of the nutrient mass across all nutrients, for all species studied.

In order to estimate the biomass availability in the CWDM, *Eucalyptus cladocalyx* and *Acacia karroo* were selected as the main species for energy wood production in an SRC system (see Von Doderer, 2009). The selection of the appropriate species depends, *inter alia,* on climate, site, ground and soil conditions, and cycle length, as well as on the production system. In turn, these factors influence growth rate, tree component distribution and the chemical composition of the biomass.

To exacerbate matters further, the chemical composition of the different components of trees varies significantly. Vassilev et al.'s overview (2009) of the chemical composition of biomass for a variety of tree species illustrates how the bark, wood, and other biomass constituents differ.

Table 5: Chemical composition and component distribution of the bioenergy tree

Ultimate analysis	**Wt.% (dry basis)**		**Proximate analysis**	**Wt. % (dry basis)**
Carbon (C)	48.00 (45-50)		Volatile matter	(80-90)
Hydrogen (H)	5.80 (5-7)		Fixed carbon	(6-18)
Nitrogen (N)	0.25 (0.1-0.4)		Ash	(0.2-5.0)
Oxygen (O)[a]	42.69 (40-45)		**Component Distribution[c]**	**Wt.%**
Sulphur (S)	0.01 (0.0-0.2)			
Ash	3.25 (1-5)		Bark	10.00
			Branches	20.00
HHV (MJ/kg)	19.00 (18.00-20.00)		Stemwood	70.00
Basic Density (kg/m^3)[b]	720 (600-900)		Sum	100.00

Notes:

[a] Calculated by difference as assumed, *inter alia*, by Corujo et al. (2010) and Channiwala and Parikh (2002).

[b] Cold-tolerant species, suitable for study area (see Von Doderer, 2009).

[c] Biomass component distribution extrapolated from cold-tolerant species as discussed in Dovey (2009), taking the relatively young age of the stand at the time of harvesting into account (Kumar et al., 2011).

However, given the vast area of study, as well as the heterogeneity thereof (including climate, ground and soil conditions), it was necessary to keep the variables for the bioenergy feedstock to a minimum, while retaining representivity to some degree for the above-mentioned species. Hence, it was decided to use a hypothetical mix of bioenergy trees comprising the same attributes, except for the growth rate, which differs for the various production areas. Table 5 shows the assumed main attributes of the 'bioenergy-tree' for the CWDM. The values in brackets are typical for other hardwood species found in the literature (Senelwa and Sims, 1999; Channiwala and Parikh, 2002; Guerrero et al., 2005; Turn et al., 2005; Garcìa-Pérez et al., 2007; Khodier et al., 2009; Munalula and Meincken, 2009; Vassilev et al., 2009; Corujo et al., 2010; Oasmaa et al., 2010; Venderbosch and Prins, 2010; Amutio et al., 2011; Bridgwater, 2011; Kumar et al., 2011; Sevilla et al., 2011).

2.4.3 Moisture content

An important consideration when it comes to bioenergy is the moisture content of the feedstock. The moisture content of solid biofuels varies widely, depending on the time of harvesting; the location, type and duration of storage; and the feedstock pre-processing. The moisture is relevant not only concerning the calorific (heating) value of the biomass but also concerning its storage conditions, combustion temperature, and the amount of exhaust gas released during the energy conversion process.

Two methods (dry and wet basis) are commonly used to specify the total moisture content. It is important to distinguish between them, especially when the moisture content is high.

Equation 1: Moisture content of biomass (dry basis)

$$Moisture_{dry\ basis} = 100x\frac{Wet\ Weight - Dry\ Weight}{Dry\ Weight}$$

Equation 2: Moisture content of biomass (wet basis)

$$Moisture_{wet\ basis} = 100x\frac{Wet\ Weight - Dry\ Weight}{Wet\ Weight}$$

In the above expressions, wet weight refers to the burned condition and dry weight refers to the wood after a standardised drying process. It is important to state the basis on which total moisture content is measured. Mostly, the bioenergy feedstock moisture content is measured on a dry basis, and this method has also been used throughout this study.

Moisture content is the most commonly used property of fuel wood. Its quantity is inversely proportional to the amount of heat that is recovered from conventional combustion, where the latent heat of evaporation is lost with flue gases (Nurmi, 1992: 160).

2.4.4 Heating value/energy content

An important fuel property is the energy content, often expressed in megajoule per kilogram (MJ/kg). The standard measure of the energy content of a fuel is its heating value (HV), also called calorific value or heat of combustion. There are multiple measurements for the HV, depending on whether it measures the enthalpy of combustion (ΔH) or the internal energy of combustion (ΔU), and whether for a fuel containing hydrogen, water is accounted for in the vapour phase or the condensed (liquid) phase. With water in the vapour phase, the lower heating value (LHV) at constant pressure measures the enthalpy change due to combustion (Jenkins et al., 1998). The heating value is obtained by the complete combustion of a unit quantity of solid fuel in an oxygen-bomb colorimeter under carefully defined conditions. The gross heat of combustion or higher heating value (GHV or HHV respectively) is obtained using the oxygen-bomb colorimeter method, where the latent heat of the moisture in the combustion phase is recovered (Demirbas, 2009b).

Hence, it is important to distinguish between the higher heating value (HHV), which refers to the energy content of absolutely dry biomass after a standardised drying process ('oven dry'), and the lower heating value (LHV) or effective heating value (EHV) of biofuels with a specific moisture content, where some energy is needed to evaporate the retained total moisture of the biomass as well as the total hydrogen of the fuel.

The actual net calorific value, or EHV, of biomass containing a known percentage of water can be calculated from the HHV, which for many biofuels is available in the literature. Various formulas are available in the literature to calculate the EHV, e.g. as found in (Kaltschmitt et al., 2002) or (Nurmi, 1992). The equation from the latter was used in this study:

Equation 3: Effective heating value of wet biomass

$$\boldsymbol{EHV = HHV - 2.45\ x\ \frac{MC}{100 - MC}}$$

Where

EHV is the effective heating value of wet biomass (MJ/kg dry basis);

HHV is the effective heating value of dry biomass (MJ/kg dry basis), depending on the chemical composition of the biomass;

2.45 is the energy required to vaporise water at 20°C (in MJ/kg); and

MC is the moisture content of biomass (as a percentage).

Based on the assumptions stated in Table 5, above, the calculated feedstock properties are provided in Table 6, below.

Table 6: Density and effective heating value at different moisture content levels

Moisture content (%)	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**
Density (kg/m^3)	720	792	864	936	1008	1080	1152	1224	1296
EHV (MJ/kg)	19.00	18.73	18.39	17.95	17.37	16.55	15.33	13.28	9.2

2.4.5 Biomass from dedicated energy crops

Dedicated crops are grown first and foremost for energy, though they may also produce non-energy by-products. The ideal energy crop converts solar energy efficiently, resulting in high bioenergy yields (C4 plants are more efficient converters in high light and high temperature conditions), needing low agrochemical input, having a low water requirement, and having low moisture levels at harvest (Venturi and Venturi, 2003).

When combustion is the end use of biomass, yield is probably the major decider between alternative crops, while for other end uses (e.g. ethanol production, biodiesel), quality and suitability of the crop are highly significant. The relative economic returns are likely to be the major drivers in deciding the outcome of competition for land use between bioenergy and production for food, feed and fibre. The relative returns for bioenergy compared with other land uses will be influenced by relative yields and values, which are determined by market forces and market distortions (e.g. subsidies). The yields and values of by-products (e.g. fodder) will also be significant determinants of returns (Cherubini et al., 2009).

Another important aspect in determining land use is the agronomic practices, which vary with the intensity of production. In fact, increasing the intensity of cultivation (i.e. the frequency of tillage, quantity of fertiliser, use of irrigation) increases yields, but also increases GHG emissions and can challenge the goal of sustainable production. In any case, it is clear that to be acceptable, energy crops must fall within the parameters of sustainable agriculture.

Dedicated energy crops can entail the added benefit of providing certain ecosystem services (e.g. C sequestration, biodiversity enhancement, salinity mitigation, and enhancement of soil and water quality). The value of these services will depend on the particular bioenergy system in question and the reference land use that it displaces. For example, these benefits would be high for a mixed species woodland planted in a cropping district suffering dry-land salinity as a result of historical land clearing, while on the other hand, if native tropical forests were displaced by bioenergy crops, the value of ecosystem services would be reduced (Cherubini et al., 2009).

2.4.6 Short-rotation coppice systems (SRC)

The term *SRC plantation* applies to hardwood plantations (e.g. willow, poplar, gum) which are fast growing in their juvenile phase and capable of multiplication by cuttings and stump shooting. Through intensive cultivation, these properties are utilised for the production of biomass that can be used for energy production (Serup et al., 2002).

In contrast to commercial forestry plantations, which are aimed at timber production and are characterised by long rotation cycles in order to produce high quality and dimension timber, SRC biomass production has far fewer requirements in terms of wood quality, and more emphasis is placed on the maximisation of volumetric production per time and area units (tonnes per hectare and year, t/ha/a). Hence, this is an agroforestry system where trees are grown for bioenergy and harvested when reaching the maximum mean annual increment (MAI). The MAI – mean annual increment, or growth – refers to the average annual growth a tree or a stand of trees has exhibited/experienced at a specified age (Kassier and Kotze, 2000). The MAI can be influenced, *inter alia*, by the number of trees planted per hectare and the applicable production method used. Generally, the more trees per ha that are planted, the sooner the MAI peak will be reached. The *Institute for Commercial Forestry Research (ICFR) Bulletin* (9/99) indicates, in various examples, the correlation of stems per hectare (sph) and age, when the MAI peaks (Coetzee, 1999)

SRC plantations are generally characterised by conditions such as relatively flat, obstacle-free ground, small trees of uniform size growing in straight rows, uniform road spacing (in many cases), short transportation distances to the mill (in some cases), small branches, and bark characteristics differing from those of conifers (Seixas et al., 2006: 6).

2.5 Conclusions

Chapter 2 elaborates on the geographical and physical boundaries of the study area, the Cape Winelands District Municipality (CWDM). These include parameters such as unemployment rate within the CWDM, and important climate data such as for rainfall and average temperatures. Based on previous work by the author, around 175 000 hectares were identified by means of a GIS as being suitable for the production of lignocellulosic biomass in short-rotation coppice (SRC) systems. With the aim of limiting the impact on the environment (e.g. biodiversity) and to avoid competition between food and biomass production, GIS was used to exclude non-suitable areas, most importantly areas with water limitations and ecologically sensitive areas. A land and biomass availability assessment for the CWDM resulted in an estimated annual supply of about 1.4 million tonnes of fresh woody biomass, assuming medium productivity of tree species such as *Eucalyptus cladocalyx* and/or *Acacia karoo*.

Further, Chapter 2 describes the general characteristics of trees grown in SRC systems, as well as the chemical composition thereof, which have a great impact on the production sequences in a bioenergy system, including harvesting, processing and conversion into electrical and thermal energy. The moisture content of the bioenergy feedstock plays a particularly important role, as it affects, *inter alia*, handling, transport costs, and conversion efficiency.

Due to differences in location, soil, climate, topography and availability of land within the CWDM, great variation in biomass productivity and resulting transport distances to potential conversion sites is expected. Further, the relevant bioenergy system components (e.g. harvesting system, transport system and conversion system) will have implications for, amongst others, financial viability, environmental impact and socio-economic considerations (e.g. employment creation potential), and as a result, for determining the most viable bioenergy system. This requires a systematic and comprehensive approach that is capable of organising and synthesising relevant information, leading to a transparent and reproducible process for determining the most viable bioenergy system.

3 CHAPTER: LITERATURE REVIEW

3.1 Introduction

The previous chapter gave background information on the availability of land and the resulting biomass productivity in the Cape Winelands District Municipality (CWDM), as well as on important lignocellulosic biomass characteristics relevant particularly for the bioenergy conversion processes. Variations in location, biomass availability and transport distances to potential bioenergy conversion sites – due to differences in location, soil, climate and other factors – result in implications for selecting the appropriate bioenergy system components and, thus, for financial viability, environmental impact and socio-economic considerations.

The life-cycle analysis (LCA) method provides a sound and widely accepted approach for detailed analyses of complex systems such as is the case with bioenergy systems. Multi-criteria decision making analysis (MCDA), on the other hand, is a useful tool for integrating the generated information for further assessment and evaluation. This literature review presents the relevant literature consulted throughout the period of the research. The aim is to orientate the reader with the aid of the relevant literature.

3.2 Life-Cycle Assessment

The heightened awareness of the importance of environmental protection, and the possible impacts associated with products (including product systems and service systems) manufactured and consumed has increased interest in the development of methods to better comprehend and reduce these impacts (ISO 14040, 1997: iii). Life-cycle assessment (LCA) has been postulated as an important and comprehensive technique. In an LCA study, the whole system involved in the production, use and waste management of a product or service is described (Baumann and Tillman, 2004: 19).

LCA can assist in (ISO 14040, 1997: iii)

- Identifying opportunities for improving the environmental aspects of products at various points in their life-cycle;
- Decision-making in industry, governmental or non-governmental organisations (e.g. strategic planning, priority setting, product or process design or redesign);
- The selection of relevant indicators of environmental performance, including measurement techniques; and

- Marketing (e.g. an environmental claim, eco-labelling or environmental product declaration).

This section gives some background information on LCA, its origin, and the general structures of the methodology. Furthermore, LCA applications in agriculture, forestry and bioenergy found in the literature are briefly discussed.

3.2.1 Origin of LCA

Mainly packaging and waste management, as well as the oil crisis and the energy debate at the beginning of the 1970s have been the drivers of LCA. Pioneers are primarily from industrialised countries such as the USA, the UK, Germany and Sweden. Generally accepted as the first LCA study was a study on the consequences of packaging and manufacturing beverage containers by the Midwest Research Institute on behalf of Coca Cola (Baumann and Tillman, 2004). At the same time, other studies were initiated in Europe in both the private (Tetra Pak) and public (German Federal Ministry of Education and Science) sectors. Although public interest waned due to the ending of the energy crisis, private businesses and certain industries (e.g. product design) remained interested. With increased interest in environmental issues in the mid 1980s, the relevance of LCA rose again. The 1990s were characterised by the harmonisation and standardisation of the LCA methodology (e.g. ISO standards 14040-14044). Today, LCA represents a common environmental assessment tool and is applied in various fields, but mostly in the primary and secondary production sectors. The importance and relevance of LCA can be identified by a steadily growing LCA community. Various software suppliers, such as SimaPro, GaBi and Umberto, have developed user-friendly LCA interfaces and are specialising in data collection and the application of LCA.

3.2.2 LCA method

Life-cycle assessment can be understood intuitively as a tool for analysing the potential environmental impacts and resources used throughout a product’s life cycle (from its ‘cradle’, through its production and use, to its ‘grave’, its disposal), i.e. from acquisition of the raw material, via the production and use phases, to waste management (Baumann and Tillman, 2004: 19). As illustrated below in Figure 4, an LCA consists of four phases, namely, goal and scope definition, inventory analysis, impact assessment, and interpretation of results. Each of the LCA phases is discussed further below.

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, process or service system (ISO 14040, 1997: iii), by

- Compiling an inventory of the relevant inputs and outputs of a product, process or service system;
- Evaluating the potential environmental impacts associated with those inputs and outputs; and
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

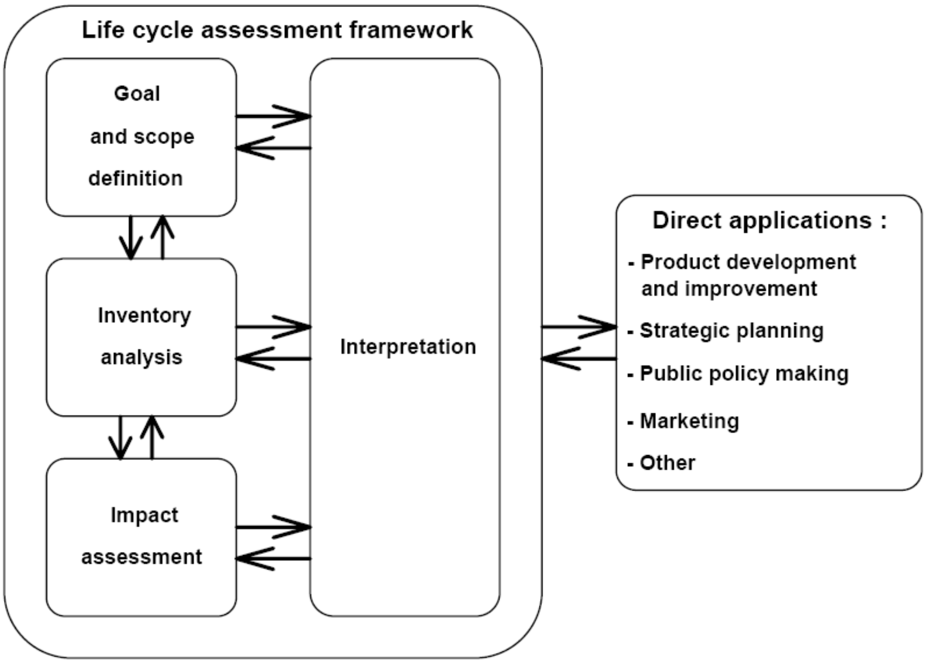

Figure 4: Phases of a life-cycle assessment

Source: ISO 14040 (1997: 4)

3.2.2.1 Goal and scope definition

The ISO standard 14041 (ISO 14041, 1998) states that the goal definition shall “unambiguously state the intended application, the reason for carrying out the study and the intended audience”. Further, it stresses that the goal and scope of an LCA study must be clearly defined and consistent with the intended application.

The scope definition also implies important considerations, such as the functional unit to be used, the product system to be studied and the product system’s boundaries, which are discussed further below.

- **Functional unit**

After the goal, the product(s) and the system have been decided on, the functional unit needs to be defined. The functional unit corresponds with a reference flow to which all other modelled flows of the system are related. This is why the functional unit needs to be quantitative.

The functional unit provides a reference to which the input and output process data are normalised, and the basis on which the final results are presented.

Generally, four types of functional units can be found in the bioenergy-LCA literature (Cherubini and Strømman, 2011: 441):

1. Input unit related – the functional unit is the unit of input biomass, measured in terms of either mass or energy. With this type of functional unit, results are independent of conversion processes and types of end-products. This unit can be selected by referring to studies that aim at comparing the best uses for a given biomass feedstock.
2. Output unit related – here the functional unit is the unit of output, like units of heat or power produced, or kilometres of transportation provided. This type of functional unit is usually selected by referring to studies aimed at comparing the provision of a given service using different feedstocks.
3. Unit of agricultural land – this functional unit refers to the hectare of agricultural land needed to produce the biomass feedstock. This unit should be the first parameter to take into account when biomass is produced from dedicated bioenergy crops.
4. Year – results of the assessment may even be reported on a yearly basis. This type of functional unit is used in studies characterised by multiple final products, since it allows avoiding an allocation step.

Typical functional units are emissions/sequestrations per unit of energy produced, emissions/sequestrations per service provided, emissions/sequestrations per unit of biomass input, and emissions/sequestrations per unit of land required.

- **System boundaries**

The system boundaries of a product, process or service system need to be specified in terms of several dimensions (Tillman et al., 1994: 79), namely:

- Boundaries in relation to the natural system,
- Geographical boundaries,

- Time boundaries,
- Boundaries within the technical system.

Boundaries in relation to natural systems. In general, activities included in the flow model of a technical system (the inventory model) are activities under human control. However, when a flow enters (or leaves) human control, it also enters (or leaves) the technical system. While it is relatively easy for non-renewable resources such as oil and minerals to be defined in the 'cradle', i.e. during the extraction thereof, the boundaries for renewable resources, between the technical and the natural system, are less easy to draw. Renewable resources may be divided into fund resources (e.g. forests and agricultural land) and flowing resources (e.g. solar radiation and fresh water streams).

In many cases, the boundary between the technical and the environmental system is obvious. However, when the life cycle includes forestry, agriculture, emissions to external wastewater systems and landfills, the system boundary needs to be explicitely defined (Finnveden et al., 2009: 5).

Particularly in the context of assessing bioenergy systems, **geographical boundaries** are an important consideration, since certain types of biomass feedstock may be limited to certain areas, and productivities may differ from area to area, *inter alia*, limited by the availability of water, climate, soil or terrain conditions. Furthermore, infrastructure such as electricity production, waste management and transport systems vary from one region to another.

Considering the **time boundaries** when defining the goal and scope of the study is an important aspect of the LCA, as it defines the type of LCA study concerned. Change-oriented LCAs are prospective. They look forward in time, since they are about alternative choices of action. Accounting LCAs ask what environmental impact a product may be made responsible for; hence, they are retrospective (Baumann and Tillman, 2004: 81).

Boundaries within the technical system relate, *inter alia,* to production capital and personnel. Whether the environmental impact from production and maintenance of capital goods should be included in an LCA has been debated. For accounting LCAs, the guiding idea is often that the study should be as complete as possible, and the production and maintentance of capital goods should thus be included. For change-oriented LCAs, whether or not capital goods will be affected by the change has to be considered. A topic that is similar to that of capital goods is that of personnel. Processes require personnel, and personnel need food, transportation and so on. Personnel-related environmental impacts are usually not included in an LCA (Baumann and Tillman, 2004: 82).

Boundaries within the technical system include those in relation to other products' life cycles. Sometimes several products (or functions) share the same process(es). If the environmental load of these processes is to be expressed in relation to one function only, then there is an allocation problem. A detailed discussion of the types of allocation problems, the principles pertaining to allocation, and specific operational allocation methods can be found in Baumann and Tillman (2004: 83-88, 110-119).

3.2.2.2 Life-Cycle Inventory (LCI)

The inventory analysis involves data collection and calculation procedures to quantify the relevant inputs and outputs of a product system. These inputs and outputs may include the use of resources and releases to air, water and land associated with the system (ISO 14040, 1997).

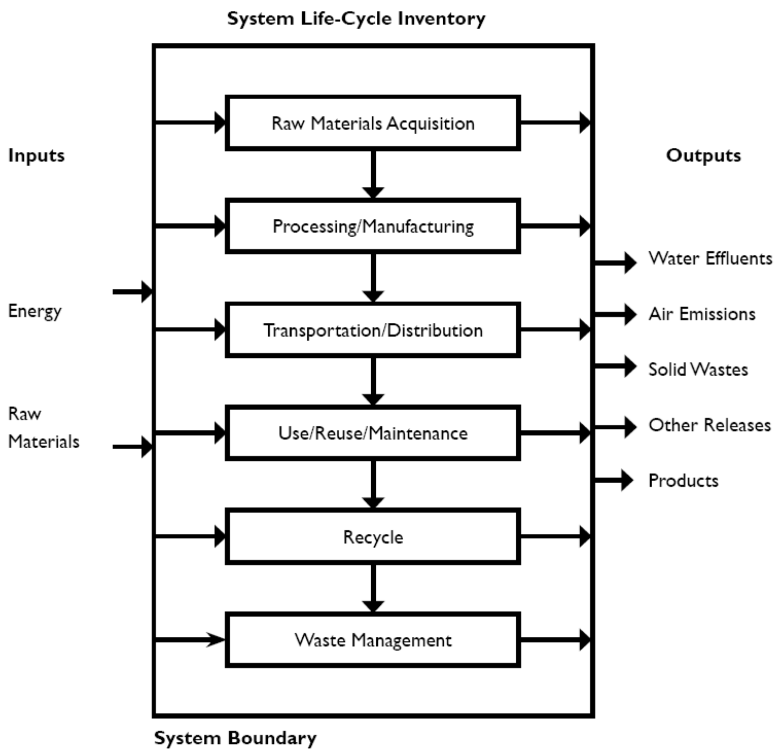

Figure 5: Scheme of the main steps and flows involved in an LCA

Source: Bird et al. (2010: 57)

Thus, a system model needs to be built according to the requirements of the goal and scope definition. The systems model is the flow model for a technical system with certain types of system boundaries ('cradle-to-grave'). The result is an incomplete mass and energy balance for the system. It is incomplete in the sense that only the environmentally relevant flows are considered, which more or less include the use of scarce resources and the emissions of substances considered harmful. Environmentally indifferent flows such as water vapour emissions from combustion or industrial surplus heat are disregarded. Figure 5, above, is an illustration of the main steps and flows involved in an LCA.

3.2.2.3 Life-Cycle Impact Assessment (LCIA)

The impact assessment phase (LCIA) follows the LCI and involves an assessment of all relevant environmental impacts associated with the input and emissions mapped in the LCI. The LCIA thus also covers other chemically related impacts like global warming and tropospheric ozone formation, as well as the physical impacts on the land and input-related impacts or the availability of resources (Birkved and Hauschild, 2006; Wenzel et al., 1997; Hauschild and Wenzel, 1998). The level of detail, choice of impacts evaluated and methodologies used depend on the goal and the scope of the study (ISO 14040, 1997).

The purpose of the LCIA is to provide additional information to help assess the results from the LCI so as to better understand their environmental significance (ISO 14040, 1997). Thus, the LCIA should translate the inventory results into their potential impacts in what are referred to as the 'areas of protection' of the LCIA (Consoli et al., 1993), i.e. the entities that are to be protected by using the LCA. Today, there is acceptance in the LCA community that the areas of protection offered by the LCA are human health, the natural environment, natural resources, and to some extent, the man-made environment (Udo de Haes et al., 2002; Finnveden et al., 2009).

As mentioned above, the 1990s were characterised by the harmonisation and standardisation of the LCA methodology. Part of this process was the development of the LCIA method and consensus building, as was done in consecutive international working groups in SETAC, the Society of Environmental Toxicology and Chemistry (SETAC, 1993). Yet LCIA is a discipline still undergoing vibrant development (Finnveden et al., 2009).

Today, several LCIA methods are available, and there is not always an obvious choice between them (Finnveden et al., 2009). In spite of the resemblance between some of them, there can be important differences in their results, not least for toxic impacts – differences which can lead to conclusions that depend on the choice of LCIA method involved (Dreyer et al., 2003).

An important consideration for the LCIA is the spatial differentiation concerned, as the impacts caused by an emission depend on the quantity of substance emitted, the properties of the substance, the characteristics of the emitting source, and the receiving environment (Finnveden et al., 2009). The site-generic approach (or global default) followed in current characterisation modelling includes only the first two aspects, inherently assuming a global set of average/standard conditions concerning the properties of the source and the receiving environment. For truly global impact categories like climate change and stratospheric ozone depletion, this is not a problem, since the impact is independent of where the emission occurs. For the other impacts modelled in the LCIA, however, the situation can be different. They are often regional or local in nature, and a global set of standard conditions can disregard large and unknown variations in the actual exposure to stimuli of the sensitive parts of the environment (Finnveden et al., 2009: 10). Sometimes differences in the sensitivities of the receiving environment can have a stronger influence on the resulting impact than differences in inherent properties of the substance that contribute to the impact (Potting and Hauschild, 1997; Finnveden et al., 2009). At the same time, spatial differences can be reduced in the case of sources from multiple locations, particularly when these result in uniform emission distributions.

Hence, spatial differentiation can be relevant in LCIA (Udo de Haes et al., 1999), but this will increase the complexity of the LCA, requiring more information in some cases about emissions and more differentiation in the impact assessment. Whether using site-dependent factors reduces uncertainty compared with using generic defaults depends on the impact category of concern, and it may also depend on the case in question (Finnveden et al., 2009).

3.2.2.4 Interpretation

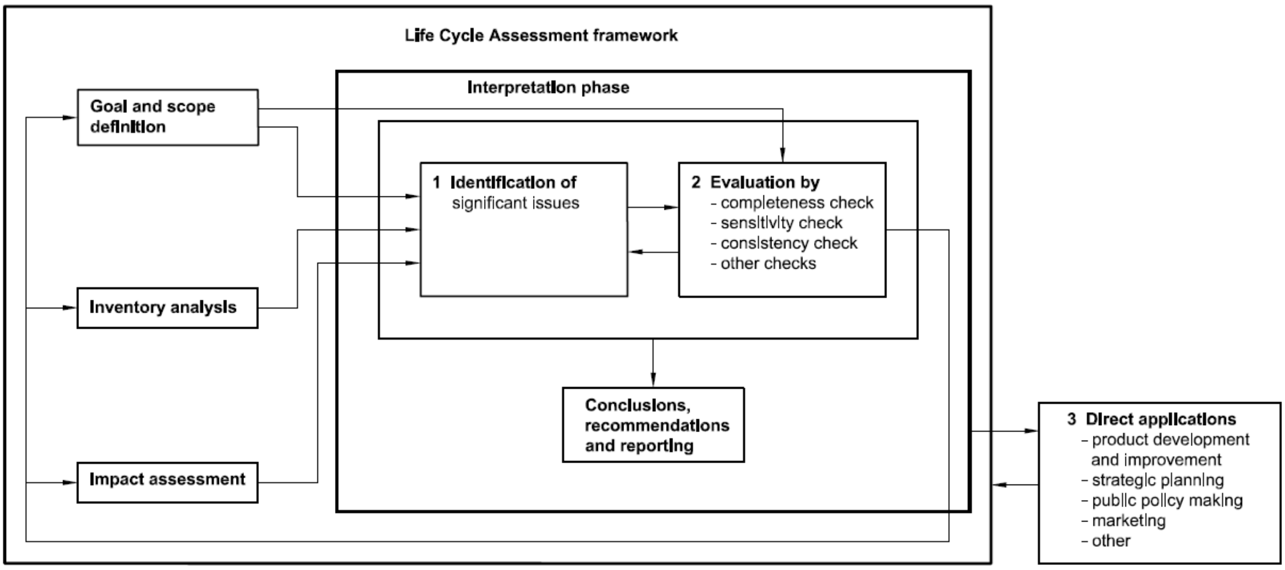

Figure 6: Relationships of the elements within the interpretation phase with the other phases of LCA

Source: ISO 14043 (2000: 4)

The objectives of the life-cycle interpretation are to analyse results, reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phases of the LCA or LCI study, and to report the results of the life-cycle interpretation in a transparent manner. Furthermore, the interpretation phase is intended to provide a readily understandable, complete and consistent presentation of the results of an LCA or an LCI study, in accordance with the goal and scope definition of the study (ISO 14043, 2000: 3). Figure 6, above, shows the relationship of the elements within the interpretation phase with other phases of the LCA.

3.2.3 Types of LCA

Finnveden et al. (2009: 3) distinguish between two types of LCAs: attributional and consequential LCAs. The attributional LCA is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems. The consequential LCA is defined by its aim of describing how environmentally relevant flows will change in response to possible decisions (Curran et al., 2005). Similar distinctions have been made in several other publications, but often using other terms to denote the two types of LCA, and sometimes including further distinctions of subcategories within the two main types of LCA (Guinée et al., 2002a). Baumann and Tillman (2004: 63), for instance, distinguish at least three types of LCAs:

- LCAs of the accounting type
- LCAs of the change-oriented type
- Standalone LCAs

LCA studies of the accounting type are comparative and retrospective. This type of LCA is well suited to different types of eco-labelling and can be used in purchasing or procurement situations, since these applications involve a comparison of existing products. LCA studies of the change-oriented type are comparative and prospective. This makes them useful in product development, building design and process choices, since decision-making involves a comparison of options that may be implemented or produced in the future. A standalone LCA is used to describe a single product, often in an exploratory way in order to get acquainted with some important environmental characteristics of that product, identifying the 'hot spots' in the life-cycle, i.e. which activities cause the greatest environmental impact (Baumann and Tillman, 2004: 63). Examples of applications for different types of LCA methodologies are presented in Table 7, below.

In general, the attributional method is the most used in LCA, but in LCA of bioenergy systems the consequential methods appears as the most broadly applied. Almost three-fourth of relevant studies reviewed by Cherubini and Strømman (2011) compare the environmental impacts with those of a fossil reference system, as they are aimed at addressing the needs of policy makers, since consequential LCA is more relevant for decision-making.

Table 7: Examples of life-cycle approaches for different applications

	Type of LCA			
Producers/ users of LCA information	**Life-cycle thinking[a]**	**Standalone LCA[b]**	**Accounting-type LCA[c]**	**Change-oriented LCA[d]**
Public policy makers/ authorities	• Development of environmental policies (e.g. producers' take-back schemes, recycling schemes and targets)	• Basis of development of producer take-back schemes	• Governmental procurement • Development of eco-labelling criteria	• Basis for development of environmental policies (e.g. recycling schemes and targets)
Industry	• Supply-chain management • Product development • Building design and construction	• Identification of 'hot spots' • Environmental product declaration (based on standardised methodology)	• Purchasing • Market communication • Development of methodological standard for environmental product declaration	• Product development • Building design and construction • Process choices and optimisation • Market communication
Environ-mental NGOs	• Development of campaign ideas	• Critical evaluation of environmental strategies and measures	• Development of eco-labelling criteria	• Critical evaluation of environmental strategies and measures
Consumers	• Lifestyle choices		• Eco-labelling (as users)	

Source: Baumann and Tillman (2004: 65)

Notes:

[a] Life-cycle thinking is less of an 'ordinary' type of quantitative LCA study, but can be described as a way of thinking that considers the cradle-to-grave implications of different activities without going into the detail of an LCA study. The principle of life-cycle thinking is often inscribed in the environmental policy of many companies.

[b] Can be characterised as descriptive.

[c] Can be characterised as comparative and retrospective.

[d] Can be characterised as comparative and prospective.

3.2.4 LCA applied in agriculture

An increasing number of LCA studies focus on applications in the agricultural context. A selection of LCA studies focussing on the agricultural context are listed in Table 8, below, subdivided into application area, year of publication, author(s), study area and a brief description of the respective study. The listed studies deal, *inter alia*, with conventional agricultural activities such as grain production, grape production/wine farming, fruit farming and related products, conventional and organic milk production or production of related products, and animal production.

As mentioned above, setting geographical as well as technical system boundaries, as well as defining the functional unit have a great effect on the outcome of life-cycle assessments. Particularly LCA studies in the primary sector are affected by local differences such as land productivity, resource availability, production systems and degree of mechanisation, and variations in the energy supply mixes. This creates a significant challenge when comparing different LCA studies.

Table 8: Application of LCA in the agricultural context

Application Area	Year	Author(s)	Study area	Description
Animal production/ products	2005	Basset-Mens and van der Werf	France	Current and alternative systems of pig production
	2005	Van der Werf et al.	France	Production and on-farm delivery of concentrated feed for pigs
	2011	De Boer et al.		Review of studies on emissions from animal production
	2011	Devers and Kleynhans	Belgium, RSA	Comparison of Flemish and Western Cape pork production
Dairy production/ products	2000	Haas et al.	Germany	Grassland dairy farming differentiated in production intensities
	2002	Berlin	Sweden	Production of semi-hard cheese
	2003	De Boer		Review of studies on conventional and organic milk production
Fruit production/ products	2006	Milà i Canals et al.	New Zealand	Apple production
	2006	Mouron et al.	Switzerland	Life-cycle management on Swiss fruit farms: relating environmental and income indicators for apple-growing
	2007	Mourad	Brazil	LCI of two perennial crops: green coffee and orange juice
	2008	Pizzigallo et al.	Italy	Assessment of two wine farms (organic and semi-industrial) in the Siena territory
	2009	Cholette and Venkat	Italy	Logistical options for delivering wine to consumers
Grain production	2004	Brentrup et al.		Adapted LCA for plant nutrition in arable crop production
	2009	Meisterling et al.	USA	Conventional and organic wheat production
Sugar beet production/ products	2001	Brentrup et al.	Germany	Sugar beet production under different fertilisation schemes
	2005	Tzilivakis et al.	UK	Environmental impact and economic assessment of sugar beet production systems
Vegetable production/ products	1998	Andersson et al.	Sweden, Italy	'Hot-spots' of tomato ketchup production
	2011	Cellura et al.	Italy	Protected crops: peppers, melons, tomatoes, cherry tomatoes, and zucchini in different types of greenhouses (tunnel and pavilion)

A significant number of LCA studies deal with the production of energy crops aimed at producing biofuels such as bio-oil, bio-diesel or bio-ethanol. Among others, crops such as barley, wheat, rapeseed, sunflower and whole cropping systems, as well as sugar crops such as sugar beet or sugar cane are investigated (refer to Table 9, below).

Table 9: Application of LCA in the agricultural energy crop context

Application area	Year	Author(s)	Study area	Description
Grain, oil seed	2005	Kim and Dale	USA	Corn and soybean production for biofuels, applying different cropping systems
Grain	2005	Lechón et al.	Spain	Agricultural production of wheat and barley grain for biofuels
Oil seed	2007	Gasol et al.	Spain	LCA of a Brassica carinata bioenergy cropping system
Grain	2008	Kim and Dale	Various countries	Fuel ethanol from corn grain via dry milling
Various	2010	Börjesson and Tufvesson	Northern Europe	Energy efficiency, greenhouse gases and eutrophication of biofuels from agricultural crops
Oil seed	2010	Iriarte et al.	Chile	Environmental impacts, energy and water demand of rapeseed and sunflower
Sugar cane	1999	Mohee and Beeharry	Mauritius	Energy generation from sugarcane bagasse
Sugar cane	2001	Beeharry	Mauritius	Greenhouse gas mitigation potential of sugarcane bioenergy systems
Sugar cane	2008	Macedo et al.	Brazil	Production and use of bioethanol from sugarcane
Sugar cane	2009	Luo et al.	Brazil	Bioethanol from sugarcane

3.2.5 LCA applied in forestry

A variety of LCA studies also deal with forestry, forestry products, or different forestry production phases, such as harvesting, forwarding or secondary transport. The increasing interest in short-rotation-coppice (SRC) systems is also reflected by the increasing number of LCA studies investigating the environmental impact of such bioenergy plantations. Table 10, below, entails a selection of LCA studies concerned with forestry operations and related products, as well as SRC plantations.

Table 10: Application of LCA in the forestry context

Application area	Year	Author(s)	Country of application	Nature and context of the problem
Forestry operations	1997	Berg	Sweden	Energy use and environmental impact of forestry operations
	2005	Berg and Lindholm	Sweden	General aspects of forestry operations
	2003	Klvac et al.		Energy audit of wood harvesting systems
	2007	Lawes et al.		Impact of colonial logging and recent subsistence harvesting in Afrotemperate forests
Forestry operations/ products	2001	Karjalainen et al.		Energy, carbon and other material flows of forestry and forest products
Forestry products	2003	Jungmeier et al.		Energy aspects in LCA of forest products
	2006	Nebel et al.	Germany	Wood-laminated floorings
Secondary transport	2009	González-García et al.	Sweden	Comparative environmental assessment of wood transport models: a case study of a Swedish pulp mill
	2000	Forsberg	Sweden, the Netherlands	Comparison of biomass energy transport systems using LCA
Short-rotation coppice (SRC)	1999	Börjesson	Sweden	Maximisation of environmental benefits of energy crop cultivation (SRC forest and energy grass)
	2003	Heller et al.		Willow SRC plantations for bioenergy production
	2007	Gruenewald et al.	Germany	Agroforestry systems for the production of woody biomass for energy transformation purposes
	2010	Roedl, A.	Germany	Production and energy utilisation of wood from SRC plantations
	2011	Fiala and Bacenetti	Italy	Economic, energetic and environmental impact in SRC harvesting operations

3.2.6 LCA applied in biofuel and bioenergy systems

While only a relatively small number of LCA studies focus solely on agriculture and forestry, LCAs applied to whole biofuel/bioenergy systems receive much greater attention. This does not come as a surprise, since comparing the environmental impacts of a certain system to the environmental impacts of a reference system, both providing the same type of product or service, is one of the core aspects of an LCA. In bioenergy, this means that the selected bioenergy system is compared with a fossil reference system (Schlamadinger et al., 1997). In Figure 7, below, the full fuel chains of a bioenergy (left side) and a fossil (right side) system producing electrical and thermal energy are compared (Bird et al., 2010). Table 11, below, lists a variety of LCA studies investigating the environmental impacts of biofuel and bioenergy systems that use, among others, different types of feedstocks, conversion technologies, and whole bioenergy systems. In general, a distinction can be made between annual and perennial crops, where the former is assumed to be an intensive production system and the latter an extensive production system. The former is often converted using biochemical processes, while the latter is mostly converted using thermochemical processes (refer also to section 4.3.1.7).

Table 11: Application of LCA in the biofuels and bioenergy context

Application area	Year	Author(s)	Study area	Description
Bioenergy	1999	Hartmann and Kaltschmitt	Germany	Electricity generation from solid biomass via co-combustion with coal
	2004	Corti		Performance analysis and LCA of biomass-integrated gasification combined cycle with reduced CO_2 emissions
	2005	Carpentieri et al.		LCA of integrated-biomass gasification combined cycle with CO_2 removal
	2006	Botha and von Blottnitz	South Africa	Comparison of sugarcane-based production of electricity and fuel ethanol
	2009	Varun et al.		Review of LCAs on renewable energy for electricity generation systems
	2010	Caserini et al.	Italy	LCA of domestic and centralised combustion
Biofuels	1997	Kaltschmitt et al.		LCA of biofuels under different environmental aspects
	2005	Gnansounou et al.		Blending of wheat-based bioethanol
	2005	Larson		Review of LCA studies on liquid biofuels for the transportation sector
	2006	Bernesson et al.	Sweden	Comparing large- and small-scale production of ethanol for heavy engines
	2006	Fredriksson et al.	Sweden	Incomplete LCAs of systems making organic farms self-sufficient in farm-produced biofuels
	2006	Pehnt		Dynamic LCA of renewable energy technologies
	2007	Von Blottnitz and Curran		Review of assessments conducted on bioethanol as a transportation fuel
	2007	Zah et al.		Environmental assessment of biofuels
	2009	Cherubini et al.		LCA of biofuel and bioenergy systems: key issues, ranges and recommendations
	2009	Davis et al.		Impact of biofuels
	2009	Lardon et al.		LCA of biodiesel production from microalgae
	2010	González-García et al.		Environmental profile of ethanol from poplar biomass as a transport fuel
	2011	Cherubini and Strømman		Review of the recent bioenergy LCA literature
	2011	Renó et al.		Methanol production from sugarcane bagasse
	2011	Rousset et al.	Brazil	LCA of eucalyptus wood charcoal briquettes
	2012	Nguyen and Hermansen	Thailand	Consequences of using molasses for ethanol production: system expansion for handling co-products in LCA of sugarcane bioenergy systems

A review of the recent bioenergy LCAs in the literature has been done by Cherubini and Strømman (2011) investigating state-of-the-art life-cycle assessments of bioenergy systems and future challenges for them. Besides discussing various parameters – such as functional unit, allocation methods, reference systems, the use of different input data, as well as uncertainties and the use of specific local factors – a qualitative interpretation of the LCA results is depicted, concluding that, with the exception of a few studies, most LCAs found a significant net reduction in GHG emissions and fossil fuel consumption when bioenergy replaces fossil energy.

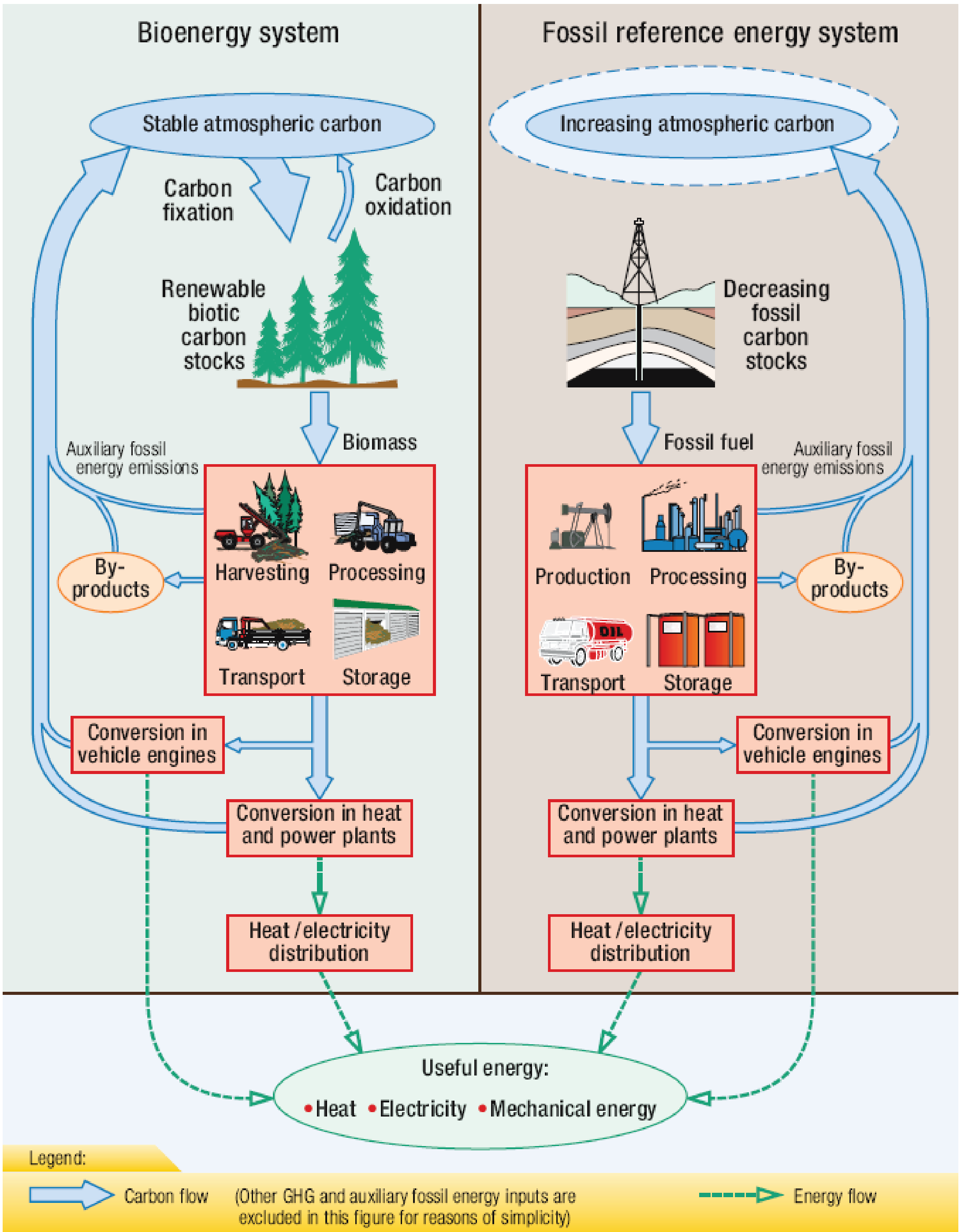

Figure 7: Full energy chains for comparison of bioenergy and fossil energy systems producing electricity and heat

Source: Bird et al. (2010: 58)

3.3 Multi-Criteria Decision-Making Analysis

Management decisions at a corporate level in both the public and private sectors will typically involve consideration of a wide range of criteria, especially when consensus needs to be sought across widely disparate interest groups. The very nature of multiple-criteria problems is that there is much information of a complex and conflicting nature pertaining to them, often reflecting differing viewpoints and often changing with time. For instance, sustainable bioenergy systems are, by definition, embedded in social, economic, and environmental contexts and depend on support by many stakeholders with different perspectives. The resulting complexity constitutes a major barrier to the implementation of bioenergy projects (Buchholz et al., 2009: 484).

In order to overcome this barrier, decision-makers are dependent on a decision support process that helps to organise and synthesise relevant information in a way that leads them to feel comfortable and confident about making a decision, minimising the potential for post-decision regret by being satisfied that all criteria or factors have properly been taken into account. Multi-criteria decision-making analysis (MCDA) is a tool aimed at aiding such a decision-making process. It can be defined as "an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter" (Belton and Stewart, 2002: 2). In contrast with cost-benefit-analysis (CBA), which relates to the use of monetary scales when confronted with multiple dimensions of management problems, MCDA – in its use of interval scaling and weights, and focussing on relative trade-offs within each dimension – avoids many of the problems associated with monetary evaluation techniques, while still permitting the assessment of potential trade-offs between criteria (Stewart, 1997: 10).

MCDA also has some desirable features that make it an appropriate tool for analysing complex problems such as are typically found in natural resource management (Mendoza and Martins, 2006: 1). First, it can deal with mixed sets of data, quantitative and qualitative, including expert opinion. Data pertaining to and knowledge about natural resource management systems are seldom complete, known with certainty, or fully understood. Hence, the ability to accommodate these gaps in information and knowledge through qualitative data, expert opinions, or experimental knowledge is a distinct advantage. Second, it is conveniently structured to enable a collaborative planning and decision-making environment. This participatory environment accommodates the involvement of multiple experts and stakeholders (Mendoza and Prabhu, 2003: 331).

In essence, the process of MCDA involves comparing management alternatives from different viewpoints (criteria), and combining these comparisons as weighted scores to obtain an overall ranking of alternatives (De Lange, 2010). The concept of an optimum, however, does not exist in a multi-criteria framework, and thus MCDA cannot be justified with the optimisation paradigm frequently adopted in traditional operational research/management science. MCDA is an aid to decision-making, a process which seeks to (Belton and Stewart, 2002: 3):

- Integrate objective measurement with value judgement, and
- Make explicit and seek to manage subjectivity.

Subjectivity is inherent in all decision-making, in particular in the choice of criteria on which to base the decision, and the relative ‘weight’ given to those criteria. MCDA does not dispel that subjectivity; it simply seeks to make the need for subjective judgements explicit and the process by which they are taken into account transparent (which again is of particular importance when multiple stakeholders are involved) (Belton and Stewart, 2002: 3).

The purpose of decision support and decision analysis, however, is not to ‘solve’ a particular decision-making problem. Rather, their purpose is to facilitate learning and understanding of the problem faced; to facilitate identifying own, other parties’ and organisational priorities, values and objectives; and to facilitate exploring these in the context of the problem. This process produces the insight that guides decision makers in identifying a preferred course of action, helping them make better decisions and promoting transparency (Laukkanen et al., 2002: 128). Fundamentally, MCDA has inherent properties that make it appealing and practically useful (Mendoza and Martins, 2006: 1).

Belton and Stewart (2002: 5) portray some of these properties as follows:

- MCDA seeks to take explicit account of multiple, conflicting criteria in aiding decision-making;
- MCDA assists in structuring the problem concerned;
- The MCDA models used provide a focus and a common language for discussion;
- MCDA facilitates decision-making by assisting the decision maker to place the problem in context, to determine the stakeholder preferences and to present the information;
- MCDA serves to complement and to challenge intuition, acting as a sounding-board against which ideas can be tested without seeking to replace intuitive judgement or experience;
- MCDA improves the legitimacy of decisions by leading to better considered, justifiable and explainable decisions, providing and audit trail for a decision.

3.3.1 Basic concepts of MCDA

Before turning to the phases of MCDA, some basic concepts of multi-criteria decision-making are briefly defined (Hobbs, 1992: 1768).

A criterion is a physical, biological, economic, or other characteristic of the alternatives that the decision makers consider important. 'Attribute' and 'objective' are common synonyms for criterion. Value scaling is the creation of single criterion value or utility functions $v_i(x_{ij})$ that convert a criterion into a measure of worth. Let x_{ij} be the value of criterion i for option j and a be the vector of values of criteria $i = \cdots, I$ for j. The creation of a single criterion value function for project costs is an example. Criterion value functions include just the decision maker's evaluations of different levels of the criterion; utility functions, in addition, capture the decision maker's attitudes toward risk. Amalgamation rules combine several single-criterion value functions $v_i(x_{ij})$ into an overall index of worth $V(a)$. An example is the additive value function, in which overall worth is the weighted sum of scaled criteria:

Equation 4: Additive value function

$$V(a) = \sum_{i=1}^{m} w_i v_i(a)$$

The weights w_i used by many rules to combine criteria are chosen by weighting methods. Some rules also ask for goals, which represent desired levels of criteria.

3.3.2 Phases of MCDA

In general, MCDA can be structured in five key phases, namely, (i-ii) problem identification and structuring, (iii-iv) model building and use, and (v) development of action plans (refer also to Figure 8). In the first two phases, problem identification and structuring, the various stakeholders, including facilitators and technical analysts, need to develop a common understanding of the problem, of the decisions that have to be made, and of the criteria by which such decisions are to be judged and evaluated. Key concerns, goals, stakeholders (classified in terms of level of interest and power of influence), actions and uncertainties need to be identified. This is the most important step in the process, since a well-structured problem is halfway solved, and since a mismatch between problem and model will lead to certain failure (De Lange, 2006: 65). Phase three and four encompass problem identification and structuring, wherein a dynamic process – after extracting the essence of the decision-making problem, the decision maker's preferences, value trade-offs, goals, and objectives, among others – is translated by a formal model allowing the alternative policies or courses of action under consideration to be compared in a systematic and transparent manner. The nature of the model will differ according to the nature of the problem and whether the alternatives are explicitly or implicitly defined. The fifth phase, the development of action plans, is concerned with implementing the results, by translating the analysis into specific plans of action. It should be reiterated, however, that the MCDA approach does not provide the ‘right answer’, even within the context of the model used, as the concept of an optimum does not exist in a multi-criteria framework.

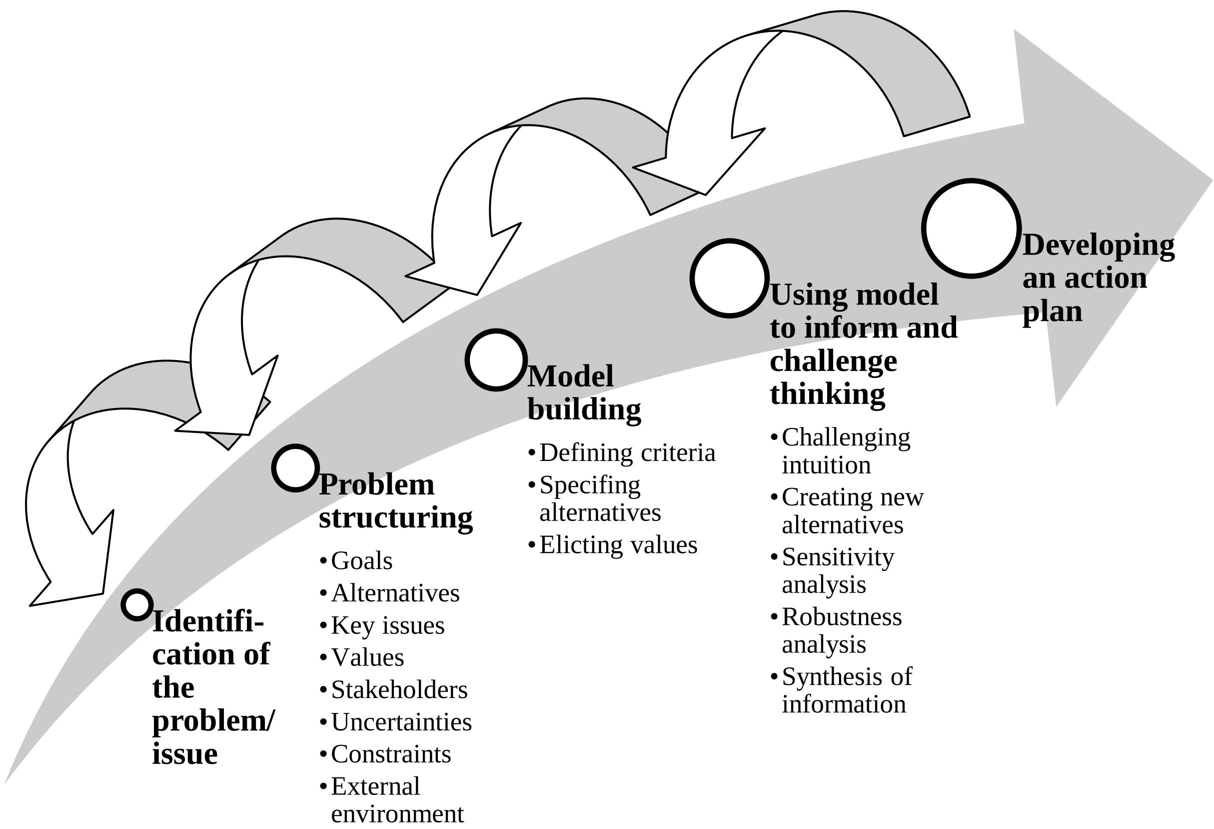

Figure 8: The process of MCDA

Adapted from Belton and Stewart (2002: 6)

Iteration within and between the key phases of an MCDA can be expected, each of which is subject to a myriad of internal and external influences and pressures. This description is generic to the whole of MCDA. However, the emphasis of an MCDA is on the second phase, model building and use. This leads to a variety of MCDA approaches, which can be distinguished by the nature of the model, the information required and how the model is used (Belton and Stewart, 2002: 7).

Although the methods of MCDA could in principle be utilised by the decision maker directly, Belton and Stewart (2002: 14) suggest that in the vast majority of non-trivial problems, the MCDA methods will be implemented by a facilitator or analyst, working with decision makers and/or interested or responsible parties. MCDA can be applied in a variety of contexts, but the output required by the user or client determines the type of MCDA used. Roy (1996) identifies four different problematiques, i.e. broad typologies or categories of problem, for which MCDA may be useful:

- The **choice** problematique – where a choice from a set of alternatives must be made;
- The **sorting** problematique – where management actions must be sorted or categorised (e.g. acceptable, unacceptable);
- The **ranking** problematique – where management alternatives must be sorted according to a given preference ordering;
- The **description** problematique – where an orderly description of actions and consequences is needed to facilitate choice.

To these, Belton and Stewart (2002: 15) add the following:

- The **design** problematique – where new management/decision alternatives are developed, meeting goals and aspirations revealed through the MCDA process;
- The **portfolio** problematique – where a subset of alternatives from a larger set of possibilities is chosen, taking the internal and external characteristics of the individual management alternative into consideration.

3.3.3 Types of MCDA

Buchholz et al. (2009: 485) distinguish between two general types of MCDA, namely, multi-objective decision-making (MODM) approaches working with an indefinite set of possible scenarios, and multi-attribute decision-making (MADM), suggesting a finite set of scenarios. For instance, linear programming follows the MODM approaches, starting with a set of principles (e.g. maximising efficiency, reducing costs) and resulting in an optimised scenario. On the other hand, MADM approaches, which are the concern in this study, start with a set of scenarios/alternatives, which are further scrutinised to determine how well they fit a set of principles. MADM approaches can be further differentiated into (Belton and Stewart, 2002: 9):

- **Value measurement models**, which assign a numerical score to each alternative, thus ranking scenarios depending on how they score according to a weighted list of criteria;

- **Goal, aspiration and reverence level models**, which are goal programming methods where 'a mathematical programming algorithm is used to approach these goals as closely as possible' (Belton and Stewart, 2002: 105);
- O**utranking models**, where the alternatives are compared pairwise to check which of them are preferred regarding each criterion (Løken, 2007). After aggregation of the results for each criterion, this approach suggests to what extent the alternatives outrank one another (Buchholz et al., 2009: 485).
- **Utility and value function approaches**, among which multi-attribute utility theory (MAUT) and analytic hierarchy process (AHP) theory are best known in South Africa (De Lange, 2006: 66).

These approaches synthesise assessments of the performance of alternatives against individual criteria (scores), together with inter-criteria information reflecting the relative importance of the different criteria (weights) to give an overall evaluation of each alternative, indicative of the decision makers' preferences (Belton and Stewart, 2002: 119). MAUT and AHP differ primarily in terms of the underlying assumptions about preference measurement, the methods used to elicit preference judgements from decision makers, and the manner of transforming these into quantitative scores (Belton and Stewart, 2002: 10). MAUT is the only technique that addresses uncertainty in its axiomatic framework by analysing the expected values. AHP assesses marginal utilities by asking for the relative strengths of preferences between each pair of possible scenarios. AHP is useful, simple and consequently, a widely used tool (De Lange, 2006: 67).

In many ways, goal programming and reference point techniques represent the earliest attempts at providing formal quantitative decision aids for complex problems involving multi-criteria decisions. Goal programming (GP) was introduced by Charnes et al. (1955). This MCDM technique is regarded as the method that operationalises the Simonian 'satisficing' approach for the achievement of a DM's objectives (Simon, 1955). A comprehensive review may be found in Lee and Olson (1999). The essential idea in goal programming is that, instead of optimising a set of objectives, the DM first sets targets for their achievement, and then an acceptable solution is found by minimising the deviations from the set of targets. The minimisation of deviations from predetermined targets can be accomplished using several alternative methods, and of these, the two most widely used ones are weighted goal programming (WGP) and lexicographic goal programming (LGP) (Rehman and Romero, 1993: 241). Reference point approaches start by having the decision maker specify achievement levels for each criterion in terms of relevant performance measures. These levels are typically of three types (De Lange, 2006: 67):

- Goal levels (performance level that will fully satisfy the goals of the decision maker);
- Exclusion levels (performance level at which, if violated, the entire scenario becomes unacceptable);
- Reference levels (expectation of the decision maker of an acceptable compromise between the conflicting demands of different criteria).

The outranking approaches differ from the value function approaches in that there is no underlying aggregative value function. The output of an analysis is not a value for each alternative, but an outranking relation among the sets of alternatives (Belton and Stewart, 2002: 233). Outranking approaches represent evidence for and against the statement that one alternative is better than another. Evidence takes the form of voting between criteria. The elimination and choice translating reality (ELECTRE) family of methods and the preference ranking organisation method of enrichment evaluations (PROMETHEE) are the two most prominent outranking approaches. Outranking approaches focus pairwise on comparisons of alternatives, and are thus generally applied to discrete choice problems (Belton and Stewart, 2002: 234).

Game theory approaches represent another type of multi-criteria decision-making where each criterion can be associated with a single player. Game theory synthesises the utility functions of individual players into a social utility function. It assumes that each criterion is associated with a particular ‘player’ and that marginal utilities can be associated with each policy scenario (Romero & Rehman, 2003: 110-113). Game theory aims at identifying solutions to the decision problem that represent the most acceptable compromise between players. Nash equilibriums – seeking the policy scenario that maximises the product of the marginal utilities – are the simplest forms of this type of approach (De Lange, 2006: 67).

The interactive multiple-criteria decision-making approach implies the progressive evolution and definition of decision makers’ preferences through interactions between them and the results generated from various runs of the model. These interactions become a dialogue in which the model responds to an initial set of the decision maker’s preferences or trade-offs, and then when this response has been examined, another set is offered, and thus the procedure progresses in an interactive and iterative way until the decision maker has found a satisfactorily outcome (Romero & Rehman, 2003: 79-102).

Further details on the concepts, approaches and other related information on MCDA can be found, *inter alia*, in Belton and Stewart (2002), Romero and Rehman (2003), Hobbs et al. (1992), Buchholz et al. (2009) and (Mendoza and Martins, 2006). Due to its simplicity, the natural appeal of expressing relative importance by means of pairwise comparisons in ratio terms, and the resulting acceptance and common application – the analytic hierarchy process (AHP) was selected for the multi-criteria decision-making assessment applied in Chapter 7.

3.3.4 MCDA applied in agriculture and forestry

Parra-Lopéz et al. (2008) use AHP to compare the different multifunctional performances (including economic, environmental, social, cultural and technical criteria) of agricultural olive production systems, with the aim of selecting the most viable system based on the concept of sustainable agriculture. Different groups of experts were tasked to assess the hypothetically greater sustainability of organic and integrated farming over conventional farming systems in the medium/long-term under average conditions in an Andalusian/Spainish context. The multifunctional performances were determined in scoring exercises using expert choice software, followed by a weighting exercise involving the identified criteria. Despite differences in the ideological tendencies of the experts, the results indicate a superior global performance of organic and integrated agriculture.

Karami (2006) also used AHP with the aim of selecting an appropriate irrigation method, determining the preference of farmers, using cluster analysis, while experts determined the priority of three irrigation methods (border, basin and sprinkler) for each group of farmers. In 74% of cases, experts confirmed the farmer's decision in selecting the irrigation method, while questioning the appropriateness of the decisions of the remaining 26% of farmers.

3.3.5 MCDA applied in biofuel and bioenergy systems

An application of MCDA in the field of renewable energy provision for the Metropolitan Borough of Kirklees in Yorkshire, UK, was done by Burton and Hubacek (2007), assessing which of small-scale or large scale-approaches could achieve energy targets in the most socially, economically and environmentally (SEE) effective way. The alternatives – solar PV, micro-hydro, micro-wind, large-scale wind, large-scale hydro, biomass, landfill gas and energy from waste – were assessed against a set of eight criteria (capital cost, operation and maintenance, generation capacity, lifespan, carbon emissions, noise, impact on the environment, and social score). The results indicate that small-scale schemes (micro-hydro, solar PV, micro-wind) are the most SEE effective, despite large-scale schemes (large-scale hydro, energy from waste, landfill gas, biomass) being more financially viable.

Another MCDA study from the UK by Longden et al. (2007) assessed the impacts of several energy-from-waste (EfW) strategies, using geographical information systems and MCDA, in the administrative areas of Cornwall and Warwickshire for developing EfW policy options. Similarly, small-scale EfW facilities score the highest overall for the chosen criteria. The study further concludes that scale is more important than technology design in determining the overall EfW policy impact.

An evaluation of the potential of MCDA to facilitate the design and implementation of sustainable bioenergy projects was performed by Buchholz et al. (2009), reviewing four MCDA tools (*Super Decisions*, *DecideIT*, *Decision Lab* and *NAIADE*), with a special focus on multi-stakeholder inclusion. Using data from a multi-stakeholder bioenergy case in Uganda, ecological (i.e. reduced completion for fertile land, reduced pollution), social (i.e. low training needs, high employment rate, diversity and certainty of ownership and business schemes, and low planning and monitoring needs), and economic criteria (i.e. increased local commerce, high cost efficiency, and high security of supply) were included. The evaluation showed that different MCDA tools may give different results, as they focus on different steps in the decision process and differ widely in their mathematical methods and structure. This highlights the importance of selecting the appropriate MCDA tool. However, in the Ugandan case study, social criteria were consistently identified by all tools as being decisive in making a bioelectricity project viable. Furthermore, the authors conclude that MCDA can assist in overcoming implementation barriers by (i) structuring the problem, (ii) assisting in identifying the least robust and/or most uncertain components in bioenergy systems and (iii) integrating stakeholders into the decision process.

An approach that sets out to support the technical-scientific decision-making process for a preliminary comparative assessment of concentrated solar thermal power (CSP) technologies was presented by Cavallaro (2009). Considering the energy sector as a key role player in achieving sustainable development and in meeting environmental goals, the selection of the appropriate CSP option required the use of decision-making tools. By applying the PROMETHEE method, 12 CSP alternatives were assessed against a set of three economic (investment costs, operating and maintenance costs, levelised electricity costs) and four technical criteria (maturity of technology, environmental impacts, temperature output, solar capacity factor). Based on input-data mainly drawn from (Pitz-Paal et al., 2004), which envisaged the installation of the CSP plant in Seville, Spain, quantitative measures apply to five of the criteria, while the remaining two, being qualitative in nature, were scored by impact scales. Following the calculation procedure, the ranking obtained showed that alternatives using hybrid solar technologies with gas were favoured, while pure thermal solar power appeared not to be competitive. Cavallaro further concludes that the decision-making process for an energy project is the closing link in the process of analysing and handling different types of information, including environmental, technical, economic and social data. Thus, MCDA can help in aiding decision-making in a technical-scientific manner, with the chosen paths being clearly and consistently justifiable.

A multi-criteria evaluation of cleaner development mechanism (CDM) projects, aimed at offsetting greenhouse gas emissions and at contributing to sustainable development in the host country, was presented by (Nussbaumer, 2009). The potential contribution to local sustainable development of 39 CDM projects was assessed by applying a multi-criteria method, in order to evaluate how labelled projects perform in comparison with similar non-labelled projects with respect to sustainability criteria. The goal of Nussbaumer’s analysis – based on the so-called multi-attribute assessment of CDM (MATA-CDM), itself underpins the multi-attribute utility theory (MAUT) framework – was purposed not at establishing a ranking among projects, but rather at comparing and discussing the contribution of initiatives aimed at promoting broad sustainable development dividends from CDM projects in relative terms. Thus, the emphasis of this study was on the scoring and on the resulting comparison of the alternatives against a set of pre-defined criteria. The weighting of the criteria and the subsequent aggregation of the weighted scores, which forms part of a conventional MCDA, were omitted, as the authors argued that the compensability of criteria would hide the potential trade-offs, which were questioned by stakeholders while the case-study was being undertaken. Furthermore, it was argued that the weighting of criteria may have been seen as arbitrary and value-driven if assigned by an individual. Each CDM project was assessed against a set of four social, environmental and economic criteria, based on the traditional ‘three pillars of sustainable development’ classification. Nussbaumer’s evaluation suggests that the sustainable development profile of ‘premium’ CDM projects tends to be comparable or slightly better than similar ordinary projects. However, the distinction between projects may very well be within the range of uncertainty intrinsic to such assessments.

3.3.6 The combined use of LCA and MCDA

By definition, LCA considers only environmental issues. In reality, however, there are also other issues, such as social, economic, political and technical issues, that cannot be ignored in any decision. Therefore, LCA should be seen in a broader context, as a tool that provides information on the product’s environmental impacts for decision-making (Miettinen and Hämäläinen, 1997: 279). Various studies have demonstrated that the structure of LCA has parallels with the decision analysis approach to decision-making (Basson and Petrie, 2007; Miettinen and Mämäläinen, 1997, Seppälä and Hämäläinen, 2001).

Aiming at covering the three main aspects of sustainability, (Valente et al., 2011) used the LCA framework to examine the environmental, economic and social impacts of the potential exploitation of woody biomass resources for energy in an Alpine forest fuel supply chain, from the forest stand to the direct heating plant. The study compares only two alternatives, a traditional and an innovative logging system and assesses them against a set of three criteria, namely, global warming potential, financial costs and direct employment potential. Although discussing a multi-criteria problem, the authors do not make use of a multi-criteria decision-making aid, but rather make use of an extended discussion of the trade-offs shown in the results.

Options for broadening and deepening LCA approaches are discussed by Jeswani et al. (2010). With the focus on strengthening LCA as a tool and to increase its usefulness for sustainability decision-making, the authors argue that there is a need to expand the ISO's LCA framework by integrating and connecting it with other concepts and methods. Among others, the paper explores procedural methods/assessment methods and analytical methods. The former, which are defined as forecasting procedural methods and are used ex ante to support the decision-making process for policies and projects, include environmental impact assessment (EIA), strategic environmental assessment (SEA), sustainability assessment (SA) and multi-criteria decision analysis (MCDA). Analytical methods include those that are used to identify and analyse the environmental, as well as social and economic impacts related to policies, projects, products and substances. Most of these methods focus primarily on one particular sustainability dimension, and are often applied as part of the assessment process. Included are environmental methods such as material flow analysis (MFA), substance flow analysis (SFA), energy/exergy analysis (EA), environmental input-output analysis (EIOA), risk assessment (RA), economic methods such as life-cycle costing (LCC), cost-benefit analysis (CBA), eco-efficiency (EE), and social methods such as social life-cycle assessment (SLCA).

One of the first attempts at integrating LCA into the decision-making process was made by Miettinen and Mämäläinen (1997), showing that approaches and tools from decision analysis would be beneficial both in planning an LCA study and in interpreting and understanding the results. To illustrate their approach, the authors used an LCA study on beverage packaging systems, combining LCA with the multi-attribute value theory (MAVT). Although economy-related criteria (e.g. investments, employment, competition, logistics), consumer-related criteria (e.g. safety, price, ease of use) and environmental criteria are discussed, only the latter were applied in the decision-making analysis, with the focus on three sub-criteria, namely, resource depletion, ecological impacts and human health impacts.

In 2006 an article by Soares et al. was published, proposing a new method for the identification of environmental impact category weights using a panel approach and MCDA in the weighting step of the LCIA. LCA results are assessed by means of MCDA, supporting a comparative evaluation, i.e. by aggregating them into single scores that synthesise the environmental scores of all the impact categories. In terms of a weighting method in the context of LCIA, the authors recognise that site-specificities, such as local or regional conditions and policies, need to be taken into account. Furthermore, the weighting method needed to be simple – in order to recalculate depending on the goal and scope of the LCA study – transparent, and simple to apply. Each life-cycle impact category (e.g. climate change, ozone depletion, abiotic resources) is scored against a set of criteria following a pair-wise comparison (distance-to-target, reversibility, duration, scale, natural resources, ecosystem health, and human health) involving weighting, employing an MCDA procedure, resulting in a single score. Again, only environmental criteria were taken into account.

An approach involving considering both technical and valuation uncertainties during decision-making, supported by environmental performance information, using on an LCA was published by Basson and Petrie in 2007. Key elements included in their approach were a 'distinguish-ability analysis' to determine whether the uncertainty in the performance information was likely to make it impossible to distinguish between the alternatives, and the use of a multivariate statistical analysis approach (principal components analysis), which facilitated the rapid analysis of large numbers of parallel sets of results and enabled the identification of choices that lead to similar and/or opposite evaluations of alternatives. In demonstrating the approach in a technology selection decision for the recommissioning of a coal-based power station (involving six design scenarios/alternatives), four main evaluation criteria were taken into consideration, namely, financial, technical, environmental and social. While including 22 sub-criteria for the environmental impact, only two sub-criteria were considered for the financial and social criteria, i.e. net present value and total number of permanent jobs, respectively. The main environmental criteria were subdivided into nine inventory-level criteria, eight eco-indicator '99 midpoint criteria (one of the LCIA impact assessment methods), three eco-indicator '99 endpoint criteria, and two additional criteria (water use and affected land footprint). The performance of the alternatives considering all evaluation criteria was compared using value function analysis. Basson and Petrie (2007) conclude that when making decisions, it is necessary to ensure that the alternatives selected for further consideration/implementation are consistent with the value systems and preferences of the stakeholders. This requires the explicit modelling of stakeholder values and preferences rather than just ‘encoding’ value judgements and preferences as part of the information used to support decision-making.

In 2010 El Hanandeh and El-Zein proposed ELECTRE SS, a modified version of the multi-criteria decision aid ELECTRE III, which modifies the exploitation phase through a new definition of the pre-order and through the introduction of a ranking index. The new approach accommodates cases where incomplete or uncertain preference data are present. The authors demonstrated the proposed approach by applying ELECTRE SS in the context of the municipal solid waste (MSW) of Sydney, aimed at identifying a strategic plan for the treatment of biodegradable waste. With the aim of minimising the quantity of waste sent to landfills, increasing energy production, and decreasing greenhouse gas emissions, ten alternatives, ranking from business-as-usual to various options for treating organic and paper fractions in MSW, were assessed. While acknowledging the multidimensional impact (environmental, economic, hazard to humans, as well as social, political and regulatory considerations), only seven criteria, subdivided into the environment (acidification gases, smog precursors), health hazards (heavy metals, dioxins) and regulations (GHG emission reduction, green energy recovery, landfilled waste) were taken into account. Performance values for all criteria were obtained through LCA modelling. The results indicate that anaerobic digestion is generally a better option than composting and incineration, mainly because of the higher rates of electricity generation and the associated credits gained for avoided emissions. Furthermore, the authors conclude that the results show the benefits of using an MCDA tool such as ELECTRE SS in combination with LCA modelling as a decision aid tool for MSW management planning under conditions of uncertainty, and that the tool could also be applied in other environmental management fields.

Further developments in the weighting and valuation of results using environmental systems analysis tools (ESATs) such as LCAs, strategic environmental assessments, cost-benefit analyses and environmental management systems are reviewed by (Ahlroth et al., 2011). Concerning weighting and valuation, with the aim of presenting such results in a comprehensible way and making alternatives easily comparable, the authors distinguish between valuation, i.e. monetary methods (e.g. market prices, avoided costs, and revealed, stated, imputed or political willingness to pay) and weighting methods based on monetary terms or value judgements (e.g. proxy, distance-to-target, panel weighting), expressed as weights. Acknowledging that there are other rationales for classifying valuation/weighting methods, the authors further discuss strategic environmental assessment (SEA), life-cycle assessment (LCA), life-cycle cost (LCC) analysis, standardised environmental management systems (EMS), system of environmental and economic accounts

(SEEA), as well as risk assessment and impact pathway analysis for decision-making with regard to the environment, in both the public and private sectors, as well as at all governance levels. Particularly in context of multi-criteria problems, LCA is referred to as a useful tool for aiding the decision-making process.

An attempt at providing a basic decision support tool for the assessment of biofuels was undertaken by Perimenis et al. (2011), testing the functionality of the tool in the case of biodiesel from rapeseed in Germany. This tool integrates the most important aspects along the entire value chain (i.e. from biomass production to bio-fuel end uses), namely, the following aspects:

- Technical (energy efficiency, feedstock conversion ratio, complexity of the system, development status/current state of the technology, and implementation potential);
- Economic (capital, consumption, operational and other related costs and revenues, including from marketing the main and by-products);
- Environmental (global warming impact and primary energy demand); and
- Social (employment creation along the entire biofuel pathway, as one of the main social drivers of the implementation of bioenergy projects (Kranjc et al., 2007)).

The decision support tool Perimenis et al. used comprises a computational component that can be combined with the personal preferences of the user. The analysis provides a score for the respective pathway, which can be used to rank different options and select from them the optimal solution. The methodology involves using a constructed spread sheet-based model in order to verify the applicability of the theoretical background. The performances of the possible alternatives in terms of the selected criteria are derived from a 'screening LCA', with the most important aspects providing the environmental input data, obtained from an economic assessment using the annuity method, as well as from technical data on the technology alternatives and the expected employment potential. The respective performances were then translated into 'grades' based on a given grade scale ('1' for a poor performance to '5' for a good performance). For the weighting of the criteria, a simplified approach was applied using pairwise comparisons, with three types of relative importance (more important, equally important and less important).

Most recently, an article by (Myllyviita et al., 2012) was accepted for the *Journal of Cleaner Production*, which assesses the environmental impacts of biomass production chains by means of LCA and MCDA. A panel which included experts in measuring the environmental impacts of biomass production was tasked with identifying and weighing the impact categories of two alternative raw materials (biodiesel and pulp production). New environmental impacts not included in the standard LCA were identified by panellists (e.g. impact on biodiversity), and higher weights were given to climate change, natural land-use change and biodiversity. Although Myllyviita et al. acknowledge potential financial implications when selecting the most promising alternative, the study focused solely on environmental criteria. The application of MCDA in determining the impact of the alternatives on biodiversity and land-use change, however, may not always be appropriate, especially when assessing wide areas with heterogeneous conditions. Alternatively, the application of GIS may be more suitable for strategic decision-making, since during GIS-based land availability assessments, 'hot-spots' such as nature reserves and other ecologically sensitive areas can be screened out, minimising the effect on biodiversity or land-use change. Besides the newly identified environmental impacts, a set of 14 environmental impact categories grounded on the ReCiPe life-cycle impact assessment method (Goedkoop et al., 2009) were used in the first phase of the MCDA, for which the simple multi-attribute rating technique (SMART), an application of an MCDA method, was applied. As for the AHP method, SMART is one of the most easily applicable MCDA methods, as it is simple and easy to modify in its application. While Myllyviita et al. concluded that it would be beneficial to include MCDA in LCA, since it results in new perspectives on traditional LCA and indicates that standard LCA may not be comprehensive. Furthermore, the authors note that utilising default weights, such as in the ReCiPe method does, and focussing only on environmental impacts can potentially lead to inaccurate results.

3.4 Conclusions

Often only monetary assessment methods such as cost-benefit analysis are used when seeking to implement alternative ways of generating energy. However, this narrow measurement of 'success' may not lead to implementation of the most sustainable alternative, as most decision-making problems are embedded not only in financial contexts but also in social, environmental and technical contexts, and depend on the support of many stakeholders with different perspectives. This is no different when seeking to implement bioenergy projects, where much information of a complex and conflicting nature, often reflecting different viewpoints and often changing with time, need to be processed. Thus, the promotion of a more sustainable pathway calls for an approach that evaluates potential alternatives in terms of a wider variety of criteria, e.g. by incorporating environmental, financial- and socio-economic factors in the decision-making process.

As shown in this literature review, the life-cycle assessment (LCA) method could aid such a decision-making process, as it provides a structured and comprehensive technique for detailed analyses of complex systems. Originally developed as an environmental assessment tool, it is aimed at capturing the environmental impacts along the entire life-cycle of a product or a service (from its cradle to its grave). The LCA method is structured in four phases, namely (1) goal and scope definition, (2) life-cycle inventory (LCI) analysis, (3) life-cycle impact assessment (LCIA), and (4) interpretation of the results. Along similar lines, in this study the goal and scope, including the various system boundary dimensions are defined in Chapter 4, and in Chapter 5, all relevant inputs and outputs of the considered systems are brought together in the life-cycle inventory (LCI). In the third phase, all potential environmental impacts associated with these inputs and outputs are evaluated, by translating the environmental loads into impacts, which makes the results more environmentally relevant, comprehensible and easier to communicate. Several LCIA methods exist, and there is not always an obvious choice between them. Common areas of protection covered by LCAs are human health, natural environment, natural resources, and to some extent, the man-made environment. However, other environmental concerns, such as impact on biodiversity and water balance, which are more difficult to specify, are not included in the LCA method. Other assessment methods dealing with these impacts, which could be potentially be integrated with LCA are described in Chapter 6. However, as discussed in section 2.3, instead of quantifying the potential impacts on biodiversity and water balance, this study deploys a geographic information system to minimise these impacts, by *a priori* excluding particularly sensitive areas.

Due to its systematic and transparent approach, LCA is well suited to being extended to measure a product's financial and social aspects along with its life-cycle. Some LCA software packages, such as GaBi 4.4, integrate additional features such as life-cycle costing (LCC) and life-cycle working environment (LCWE), allowing a quantitative assessment of the financial aspects of a product or service. This is done by tracking the various cost factors and social aspects on the basis of working time per value added relating to a process or flow throughout the product or service's life-cycle. While the conventional LCA method has reached a great level of maturity, proven by ISO standards 14040-14044 and a variety of studies assessing a multitude of products and systems across all sectors, complementary assessment methods covering financial and social aspects are still relatively immature, requiring additional research into and development of the methodological approach, particularly in terms of the definition of new indicators/assessment criteria. As is shown in this study, multi-period budgeting, a sound and proven method, particularly in the agricultural economics context, could serve as a complementary tool to LCA to assess financial viability. Instead of using LCC, which provides only limited financial-economic information in terms of cost factors, MPB models can aid the decision-making process by also providing profitability indicators such as internal rate of return (IRR) and net present value (NPV). In addition, the productivity and performance assumptions made in the LCA and the MPB can be used as socio-economic indicators to derive the employment potential for various income categories.

However, while LCA and MPB are suitable methods for providing environmental, social and financial performance data in a structured and comprehensive way, an additional method that organises and synthesises the respective information, integrating mixed sets of data and assisting decision makers to place the problem in context and to determine the preferences of the stakeholders involved is required to support decision-making. Multi-criteria decision analysis (MCDA), which is defined as umbrella term to describe a collection of formal approaches, fulfils these requirements. It does this by improving the legitimacy of decisions, leading to better-considered, justifiable and explainable decisions, while providing an audit trail for a decision. Various MCDA methods exist, generally classified as value measurement models; goal, aspiration and reverence level models; and outranking models.

Studies using a similar approach, i.e. combining LCA and MCDA to support decision-making, were discussed in the last section of this chapter. A variety of studies concur that environmental, financial- and socio-economic criteria need to be considered when seeking the most sustainable alternative. most of them fall short in their application, as they consider either only the environmental aspects (in most instances only LCA-based criteria) or they take a very limited number of financial or social aspects into account (e.g. only one for each aspect). The immaturity of complementary assessment methods, the data intensity and the lengthy process of generating the respective information are given as explanations for omitting other sustainability indicators.

By using performance data that is generated during an LCA, and complementary financial-and socio-economic assessment methods, the first part of this study (Chapters 4-6) is aimed at supporting decision-making and at minimising subjectivity and single-dimensionality by providing performance data in an objective, transparent and reproducible manner. The analytical hierarchy process (AHP) – one of the commonly applied and accepted MCDA approaches, characterised by its simplicity and possessing the natural appeal of expressing relative importance by means of pairwise comparisons in ratio terms – is applied in Chapter 7 to integrate and evaluate the performance data provided, in order to determine the most viable lignocellulosic bioenergy system for the Cape Winelands District Municipality.

4 CHAPTER: GOAL AND SCOPE DEFINITION

4.1 Introduction

The introduction of lignocellulosic biomass based bioenergy systems in the Cape Winelands District Municipality may, *inter alia*, enhance the energy supply, create employment and additional income opportunities, but may also affect the environment. Sustainability of production is key, hereby meaning the implementation of pathways that are technically efficient, financial-economically affordable, environmentally friendly and socially acceptable. Therefore, when decision makers, such as local governments, seek to determine the optimal bioenergy system, a decision-aiding approach is required, that supplies information on possible pathways over the whole life-cycle from the production and supply of biomass to the conversion into energy, in a systematic, coherent, transparent and reproducible manner. The life-cycle assessment (LCA) framework is an approach fulfilling these requirements. Thus, the intention of this life-cycle assessment is to provide information on the performance of lignocellulosic biomass based bioenergy systems for the CWDM in terms of environmental criteria, as well as in terms of financial-economic and socio-economic criteria.

The previous chapter entails, *inter alia*, a description of the life-cycle assessment framework (refer to section 3.2), subdivided in four phases, namely goal and scope definition, life-cycle inventory, life-cycle impact assessment and the interpretation of the results. Chapter 4 encompasses the first phase, the goal and scope definition, which shall "unambiguously state the intended application, the reasons for carrying out the study and the intended audience" (ISO 14041, 1998).

This chapter sets the foundation of this study by defining goal and scope and by specifying functional unit and the different dimensions of system boundaries. The latter includes also the technical system boundaries, i.e. the alternative lignocellulosic biomass based bioenergy system pathways are defined, providing also background information on state-of-the-art technologies and systems for each phase of the life-cycle.

4.2 Functional unit

The functional unit provides a reference to which the input and output process data are normalised and the basis on which the final results are presented. Similar to that in a study by Petrie et al. (2004: 381), the functional unit used in this study is a combination of functional unit types two and four (see section 3.2.2.1), i.e. a dual time and product basis is used, in which the burdens calculated for an average year's operation are normalised to the total electrical power produced per year: an annual electricity generation of 39 600 megawatt hours (MWh). This is based on a 5-MW system generating electricity for 7 920 hours per year (330 days of full production). The reasoning was to allow a direct comparison of the different alternatives, and to compare lignocellulosic-biomass bioenergy systems with the current South African energy mix.

4.3 System boundaries

As stated in section 3.2.2.1, the system boundaries in a life-cycle assessment (LCA) need to be defined in terms of several dimensions, namely, geographical boundaries, boundaries in relation to the natural system, technical system boundaries, as well as time boundaries.

The geographical boundaries are set by the political boundaries of the Cape Winelands District Municipality (CWDM), as described in section 2.2. The boundaries in relation to the natural system are specified in two ways, by describing the woody biomass feedstock and by defining the properties thereof (see section 2.3-2.4), and the biomass production capacity (per section 4.3.2). A general description of the technical system boundaries and a discussion of relevant parameters for each aspect of the life-cycle are given in the subsequent section.

4.3.1 Technical system boundaries

This section includes a general description of the technical systems of the life cycle of lignocellulosic-biomass bioenergy systems in the CWDM, which can be structured in five production phases:

(i) Primary production of biomass in short-rotation-coppice (SRC) plantations,
(ii) Harvesting and primary transportation of the biomass from in-field to the roadside,
(iii) Pretreatment of the biomass,
(iv) Secondary transport of the bioenergy feedstock from the roadside to a central conversion plant, and
(v) Further processing of the feedstock and its conversion into electricity.

Important aspects of each production phase are also discussed. Figure 9 and 10, below, are schematic illustrations of the technical system boundaries for the bioenergy systems compared. For all activities/processes throughout the life cycle, best operating practices (BOP) are assumed.

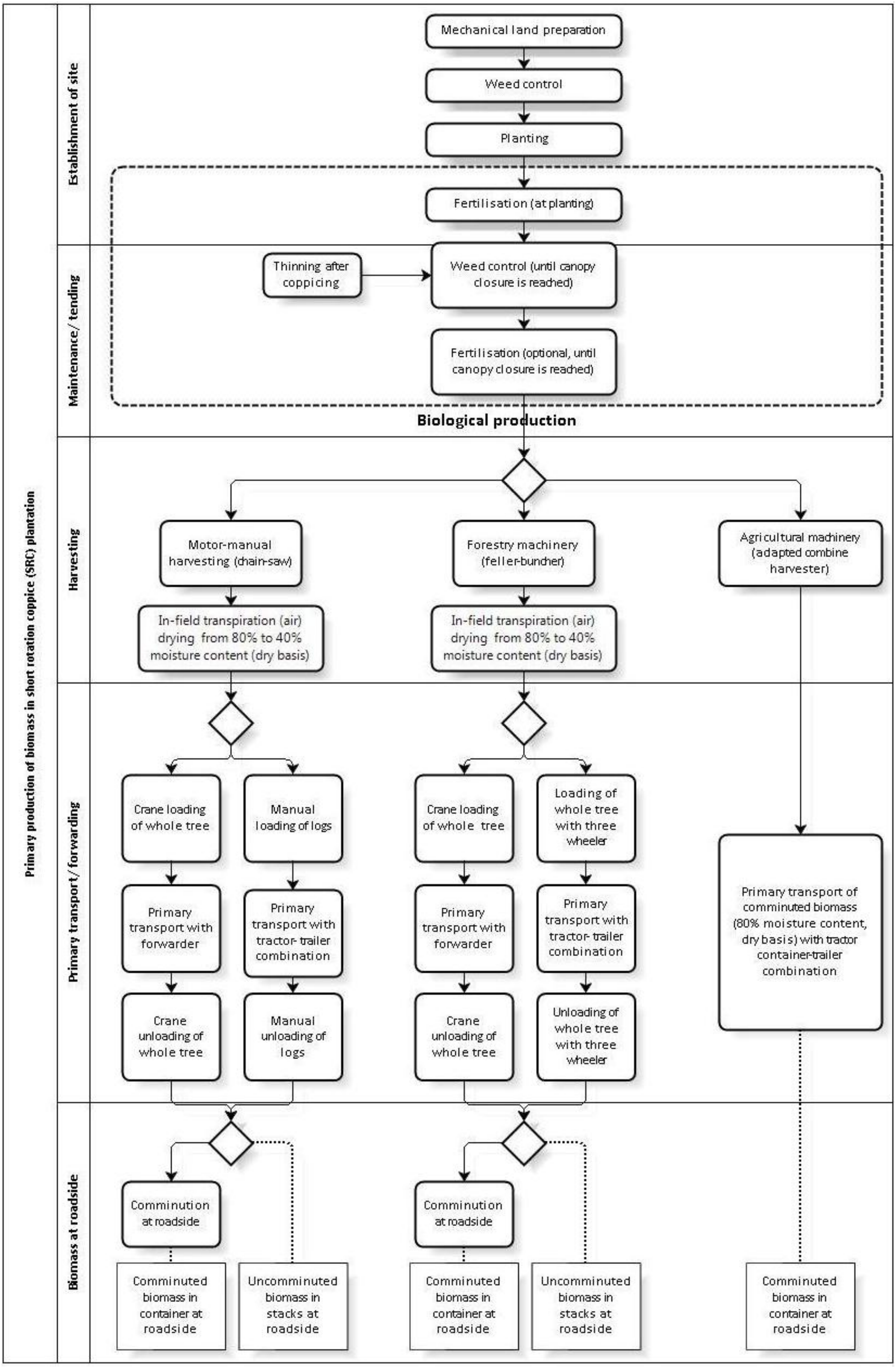

Figure 9: Technical system boundaries – schematic illustration of production phases from in-field to the roadside

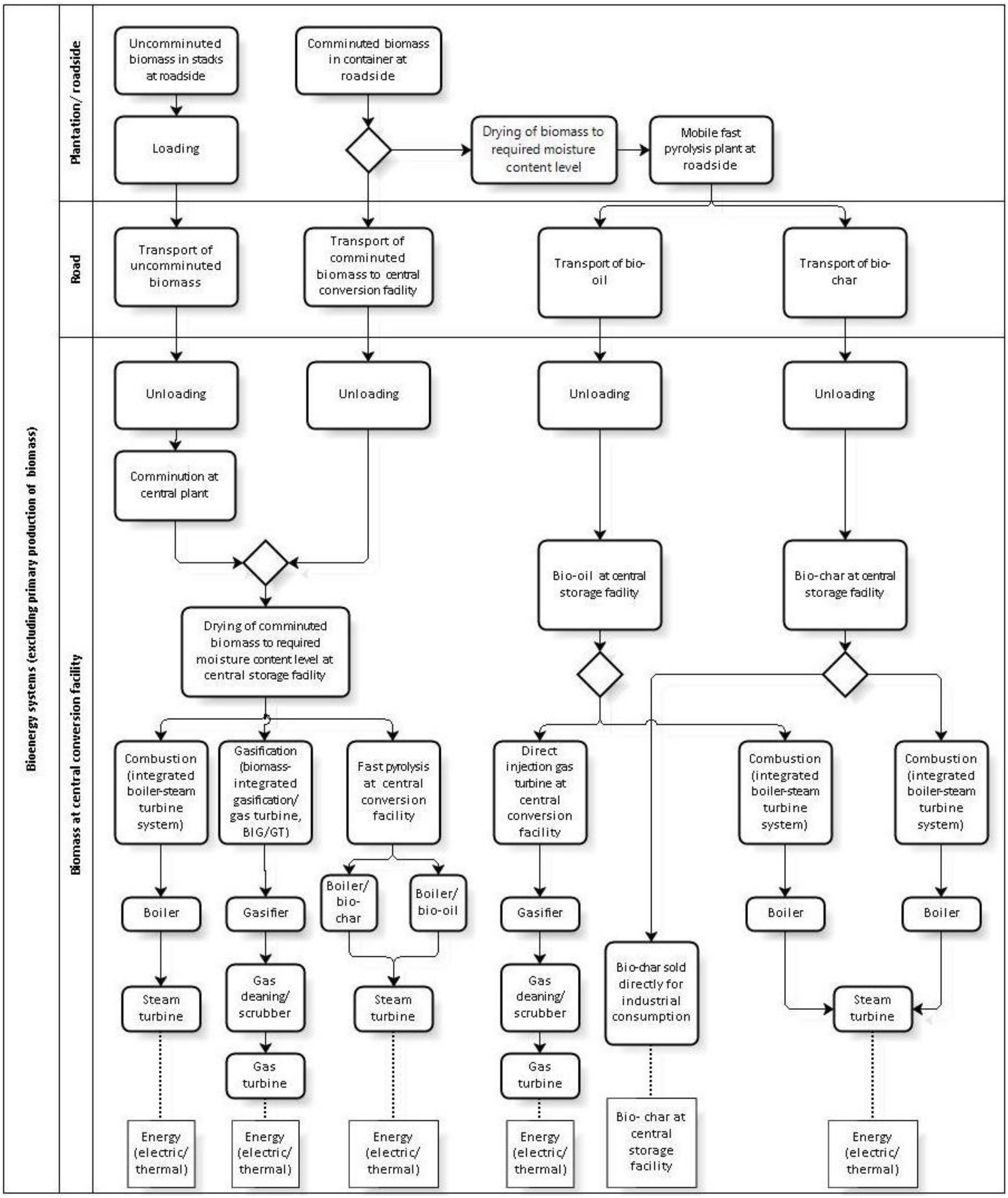

Figure 10: Technical system boundaries – schematic illustration of production phases, from roadside to central conversion facility

Figure 11, below, translates the schematic illustrations into a set of 37 separate lignocellulosic bioenergy systems (LBSs), which are characterised by different combinations: type of harvesting and forwarding in the SRC plantation, type of pretreatment (comminution, fast pyrolysis) and location thereof (roadside or landing of the central conversion plant), type of secondary transport from the roadside to the central conversion site, and type of bio-electricity generation system.

LBS	Plantation			Roadside		Road	Central Conversion Site		LBS
01	Primary Production of Biomass	Motor-Manual Harvesting (*whole tree*)	Forwarding with Forestry Machinery (*whole tree*)	Mobile Chipping of Biomass	Transport of Comminuted Biomass		Direct Combustion of Biomass		*01*
02							Direct Gasification of Biomass		*02*
03							Central Pyrolysis + Conversion		*03*
04					Mobile Pyrolysis	Transport of Mobile Pyrolysis Products	Combustion of Pyrolysis Products		*04*
05							Bio-Oil in Gas Turbine/Bio-Char sold to Industry		*05*
06				Transport of Uncomminuted Biomass			Stationary Chipping at Landing	Direct Combustion of Biomass	*06*
07								Direct Gasification of Biomass	*07*
08								Central Pyrolysis + Conversion	*08*
09		Motor-Manual Harvesting (*log*)	Forwarding with Agricultural Machinery (*manual loading of logs)*	Mobile Chipping of Biomass	Transport of Comminuted Biomass		Direct Combustion of Biomass		*09*
10							Direct Gasification of Biomass		*10*
11							Central Pyrolysis + Conversion		*11*
12					Mobile Pyrolysis	Transport of Mobile Pyrolysis Products	Combustion of Pyrolysis Products		*12*
13							Bio-Oil in Gas Turbine/Bio-Char sold to Industry		*13*
14				Transport of Uncomminuted Biomass			Stationary Chipping at Landing	Direct Combustion of Biomass	*14*
15								Direct Gasification of Biomass	*15*
16								Central Pyrolysis + Conversion	*16*
17		Harvesting with Forestry Machinery (*whole tree*)	Forwarding with Forestry Machinery (*whole tree*)	Mobile Chipping of Biomass	Transport of Comminuted Biomass		Direct Combustion of Biomass		*17*
18							Direct Gasification of Biomass		*18*
19							Central Pyrolysis + Conversion		*19*
20					Mobile Pyrolysis	Transport of Mobile Pyrolysis Products	Combustion of Pyrolysis Products		*20*
21							Bio-Oil in Gas Turbine/Bio-Char Sold to Industry		*21*
22				Transport of Uncomminuted Biomass			Stationary Chipping at Landing	Direct Combustion of Biomass	*22*
23								Direct Gasification of Biomass	*23*
24								Central Pyrolysis + Conversion	*24*
25			Forwarding with Agricultural Machinery (*loading of whole trees with three-wheeler)*	Mobile Chipping of Biomass	Transport of Comminuted Biomass		Direct Combustion of Biomass		*25*
26							Direct Gasification of Biomass		*26*
27							Central Pyrolysis + Conversion		*27*
28					Mobile Pyrolysis	Transport of Mobile Pyrolysis Products	Combustion of Pyrolysis Products		*28*
29							Bio-Oil in Gas Turbine/Bio-Char sold to Industry		*29*
30				Transport of Uncomminuted Biomass			Stationary Chipping at Landing	Direct Combustion of Biomass	*30*
31								Direct Gasification of Biomass	*31*
32								Central Pyrolysis + Conversion	*32*
33		Harvesting with Agricultural Machinery (*whole tree*)	Forwarding with Agricultural Machinery (*whole tree*)	Transport of Comminuted Biomass			Direct Combustion of Biomass		*33*
34							Direct Gasification of Biomass		*34*
35							Central Pyrolysis + Conversion		*35*
36				Mobile Pyrolysis		Transport of Mobile Pyrolysis Products	Combustion of Pyrolysis Products		*36*
37							Bio-Oil in Gas Turbine/Bio-Char sold to Industry		*37*

Figure 11: *Overview of CWDM bioenergy pathways leading to set of 37 lignocellulosic bioenergy systems (LBSs)*

4.3.1.1 Primary biomass production

The initial phase of the bioenergy life cycle is characterised by the primary production of the biomass, comprising mechanical and chemical land preparation of the SRC plantation, planting of fast-growing trees, which can be aggregated to the establishment of the site. This is followed by the maintenance of the plantation (in forestry terms also called tending). The maintenance of SRC plantations consists of weed control operations prior to and after planting, and fertilising operations in order to enhance the growth rate of the trees, particularly during the first years after planting, until canopy closure is reached, after which competition from weeds is eliminated (Little et al., 1997).

A post-harvesting activity, thinning, also forms part of the primary biomass production phase. After clear-felling a plantation, coppice shoots are allowed to re-sprout in order to regenerate the section. Once coppice shoots reach a height of between 1.5-2.0m, they should be reduced to between one or two shoots per stump (Little and Du Toit, 2003). The aim is to achieve the same tree density that was obtained in the first planting operation, relative to the stand target concerned. More than one shoot per stump can be left to make up for the mortality of neighbouring stumps (Von Doderer, 2009: 42).

As can be seen in Figure 9 and 11, above, all activities/processes prior to harvesting are assumed to be the same for all 37 bioenergy alternatives. With the exception of the mechanical land preparation, all activities/processes prior to harvesting deploy manual labour in order to minimise intermediate capital investments and the potential emissions thereof, as well as to create employment opportunities, particularly in the low-skills category.

4.3.1.2 Harvesting and primary transport

Once the maximum annual increment is reached (refer to section 4.3.2), the trees grown in SRC plantations are harvested. The harvesting and primary transportation of biomass are often aggregated in the term *harvesting system*. *Harvesting* refers to the felling of trees and, in some cases, to the in-field pretreatment thereof (e.g. de-branching, topping and cross-cutting). *Primary transport* (also referred to as *forwarding* or *extraction*) denotes the in-field movement of woody biomass (e.g. felled trees) from the stump to the forest road, roadside, or landing (collectively referred to as the *primary landing*) (Morkel, 2000).

A variety of biomass harvesting machines and systems exists (Stokes et al., 1986; Seixas et al., 2006; Spinelli et al., 2007; Spinelli and Hartsough, 2006; Ashton et al., 2007; Röser et al., 2011; Abbas et al., 2011). In general, large and highly mechanised harvesting and forwarding machinery is more cost effective than small-scale systems, due to its greater productivity, notwithstanding the high capital investment costs (Ashton et al., 2007). However, given that in most cases within the context of the CWDM biomass production will be an additional farming enterprise in an existing farming business, existing agricultural machinery and equipment may be available, and therefore preferred, since little or no additional investments will be required and greater levels of utilisation of the existing intermediate capital could be reached.

Conventional forestry equipment and systems are commonly used across the northern hemisphere to harvest SRC plantations. However, one problem of using conventional machines is tree size, since the harvesting costs are generally lower for larger trees (Seixas et al., 2006). According to Hartsough and Yomogida (1996), the best machines, mainly from Scandinavia, are based on advanced harvesters for traditional crops such as corn and sugar cane, involving relatively minor adaptions, such as headers specifically designed for harvesting small-diameter hardwoods.

Tricycle or articulated rubber-tyred drive-to-tree feller-bunchers are by far the cheapest commercially available machines for felling and bunching trees in the 10-25cm DBH range. Felling and bunching is followed by skidding, whole-tree forwarding or wood-mobile chipping. Tricycle or articulated rubber-tyred drive-to-tree feller-bunchers cause more soil disturbance than other felling methods, and cannot load onto forwarders or trailers. Rubber-tired or tracked limited-area (excavator-style) feller-bunchers are more expensive than drive-to-tree machines, but travel on a single track, causing little surface disturbance (Seixas et al., 2006).

Another recently adopted harvesting system option is the ‘harwarder’ (harvester-forwarder), a machine combining a harvester with a forwarder (e.g. Valmet 801 Combi/330 Duo, Ponsse Harwarder). The harwarder is able to compete with the harvester and forwarder system over short forwarding distances, with lower traffic movements (Seixas et al., 2006: 8). A study by Sirén (2003) compared a harwarder model with three other small harvesters especially developed for thinning. The results showed that costs were higher for harwarders than for other systems using harvesters and forwarders.

With the increasing interest in agroforestry in the late 1990s to early 2000s, particularly in Europe, initiated by the search for renewable energy supplies, alternative harvesting technologies to conventional forestry machinery were investigated. Generally, conventional forestry harvesting systems are well adapted to large trees, but not to small trees grown in an SRC plantation system, resulting in high production costs and low efficiencies. Hence, ways of harvesting were assessed to improve productivity as well as cost-efficiency. Various ‘cut and chip’ harvesters have been developed to meet these requirements. Combine harvesters have been modified and fitted with a header for harvesting short-rotation biomass. Examples of these are the Claas HS_1-HS_2, Kemper, and Krone headers (e.g. HTM WoodCut 1500), as well as the Italian-based GBE company with its GBE_1 and GBE_2 headers.

Given the local conditions and the technological suitability, five different harvesting systems (HS) combining three modes of harvesting with three types of forwarding are modelled in this study (refer also to Figure 11):

(i) Harvesting system I entails a motor-manual operation, where the trees are felled and left in-field for air-drying until a moisture content level of around 40% (dry basis) has been reached, with the whole trees being extracted using dedicated forestry machinery, i.e. a ‘forwarder’ fitted with a crane for mechanical loading and unloading.

(ii) Harvesting system II represents a manual labour-intensive option: The trees are felled, de-branched, topped and cross-cut using chainsaws, and then left for air-drying in-field. Only the logs are used for bioenergy feedstock, leaving around 30% of the biomass (branches and tops) behind (refer to section 2.4.2). Agricultural machinery, i.e. tractors coupled with modified pole-trailers are used to extract the logs. To load and unload the logs, manual labour is assumed, creating considerable employment opportunities, particularly in the low-skills segment.

(iii) A greater degree of mechanisation is assumed for harvesting system III, as dedicated forestry equipment is used for both harvesting and forwarding. A feller-buncher is used to fell the trees and bunch them in rows, butt ends facing in the same direction, allowing the forwarder to easily load by crane, and to forward the whole-trees to the roadside.

(iv) Harvesting system IV also involves using a feller-buncher for the harvesting operation, but a tractor coupled with a pole-trailer is used for forwarding. For whole-tree loading and unloading such as this, additional machinery such as three-wheeler loaders are required.

(v) Whole-tree utilisation is also assumed for the harvesting system V. Modified agricultural machinery, i.e. self-propelled forage harvesters equipped with dedicated SRC biomass harvesting heads are used to fell and comminute the trees in a single operation (see Figure 29, below). A tractor coupled with a container-trailer drives alongside the harvester, which simultaneously blows the comminuted fresh biomass into the container (see Figure 12, below).

Harvesting systems I-IV allow a time delay between felling and forwarding until the biomass has dried from 80% at the time of harvesting to around 40% moisture content (dry basis), the commonly accepted level for secondary transport. This offers several advantages, such as reduced biomass weight, and therefore, reduced costs and emissions from transporting and drying the biomass to the required moisture content levels for the respective bioenergy conversion processes. Furthermore, by storing the biomass in-field for several weeks, the felled trees defoliate to some extent. Thus, fewer nutrients are removed from the plantation. On the other hand, additional handling is required further downstream, resulting in increased resource input, costs and related emissions elsewhere in the bioenergy value chain. Drier biomass also has an adverse effect on the quality of the comminuted biomass, as the risk increases of producing under-sized particles not suitable for the bioenergy conversion process.

Figure 12: Claas Jaguar 850 with SRC biomass harvesting head

Source: Regione-Lombardia (2008)

In harvesting system V, trees are cut and comminuted simultaneously, obviating additional handling as with comminution at the roadside or the landing. Hence, both the field and the roadside are left clean after harvesting operations. Since with this system fresh biomass is comminuted, fewer under-sized particles are expected to be produced. However, since the whole tree including foliage is processed and removed from the plantation, the result is a greater loss of nutrients. Hence, additional fertilisation may be required. Another negative aspect is the increased transport costs and related emissions due to the relatively greater mass of the biomass as a result of the higher moisture content. A potential threat comes from the self-ignition of fresh chipped biomass when stored on a pile or in a container. Natural decomposing processes caused by fungi and bacteria lead to a rise in temperature, resulting not only in a loss of biomass but also potentially causing self-ignition of the biomass (Serup et al., 2002: 19). Generally, the larger the wood chips are, the slower the decomposition process is.

Three types of activities/processes are aggregated in the term biomass pretreatment, namely,

(i) Mechanical pretreatment, i.e. biomass comminution into wood chips or chunks meeting the conversion technology's feedstock particle size requirements,

(ii) Thermal pretreatment, i.e. drying of the comminuted biomass to meet the respective conversion technology's moisture content-level requirements, and

(iii) Thermo-chemical pre-processing, i.e. fast pyrolysis, where the comminuted biomass is converted into pyrolysis oil and char (also called bio-oil and bio-char).

As illustrated in Figure 9, 10 and 11, depending on the bioenergy system's configuration, all three pretreatment activities take place at the roadside or at the landing of the central conversion plant.

4.3.1.3 Biomass pretreatment: Comminution

Biomass-feedstock-based conversion technologies stipulate various requirements in terms of the physical properties of the bioenergy feedstock. These include feedstock dimensions, size distribution, moisture content, ash content, and pollutants (stones, soil, sand, etc.). In order to meet size requirements, the biomass is comminuted into a smaller, more homogeneous bioenergy feedstock (sometimes also called fuelwood) such as wood chips or chunks.

Various types of biomass comminuters exist, such as hammer mills, shredders and chippers, with the latter being the most common for biomass comminution. Chippers can be classified into three different categories: disc chippers, drum chippers, and screw chippers, differing only in their way of chipping (Serup et al., 2002: 18).

In commercial forestry systems, the comminution of biomass is considered at four locations, namely,

- At the source of the biomass, i.e. in-field,
- At the roadside, close to the source, but accessible for secondary transport,
- At a terminal in remote areas, where the biomass is concentrated for further transport to the final destination, or
- At the landing of the conversion site.

Each comminution location requires a specific machinery setup. General advantages and disadvantages are discussed in Table 12, below.

Table 12: Advantages and disadvantages of biomass comminution at different locations

	Location			
	In-field	**Roadside**	**Terminal**	**Landing**
Advantages	• Chipping and forwarding with same unit • Small roadside storage facility required • Clean areas after harvesting operations	• Chipping and secondary transportation with same unit • No hot chain • Chips can be supplied to several small plants • Small harvesting sites • Short transport distances for uncomminuted biomass	• Effective chipping operation (all season) • No hot chain • Good quality management of chips • Continuous supply ensured	• No hot chain • Large-scale production • Powerful comminution • Most cost-efficient supply chain with relatively short transport distances for chips
Disadvantages	• Ineffective chipping • Size limitation of chipper's container due to terrain • Long forwarding distances • Prone to breakdowns • Long transportation distances for chips; thus high costs and emissions	• Size and weight limitation of container • Long transportation distances for chips; thus high costs and emissions • Large storage space at roadside required • Untidy roadside storage areas after harvesting operations	• Establishment expenses of new terminal • Identifying appropriate terminal areas • Extra handling times • Relatively high total supply chain costs	• Long transportation distances for uncomminuted biomass; thus high costs and emissions • Large storage facility at roadside and landing required • Untidy roadside storage areas after harvesting operations

In Figure 9 and 10, two locations for the comminution of the biomass are presented: at the roadside and at the landing of the central conversion plant. Roadside comminution encompasses several small-scale mobile chipping systems, whereas for the latter, a single large-scale stationary chipping system is assumed.

The mobile roadside chipping system is characterised, *inter alia*, by its mobility, its user-friendliness (even small tractors can be used to power the chipper when PTO-driven, and can be operated by semi-skilled operators), and its relatively low capital investment costs. Another advantage may be that by running several mobile chippers at the same time, even if one system is not running due to maintenance, a continuous supply of wood chips can be ensured. On the other hand, mobile chippers are relatively small in size and, therefore, are less productive. Furthermore, mobile chippers are more prone to maintenance downtime as they are less robust than stationary systems (e.g. requiring sharpening or replacing of chipping blades and other spares).

Stationary chipping systems are characterised by considerably higher capital investment costs, greater complexity of the system, requiring more qualified operators, and if the system is down for a considerable period, the conversion system might be affected due to a lack of feedstock. However, due to their greater capacity, they reach higher productivity levels and are less prone to maintenance downtime, since these systems are more robust and allow for quicker maintenance and repairs.

Generally, it could be said that chipping at a central point is more cost effective than chipping at the plantation. However, the increased handling and transportation associated with centralised comminution will negatively affect the transportation cost, especially over a short distance (Johansson et al., 2006).

Wood chips are typically 5-50mm long in the direction of the fibre, and can be classified as coarse (stay in 8mm), accepts (stay in 3-7mm) and fines (pass 3mm) (Serup et al., 2002: 14). However, as mentioned above, feedstock particle size requirements depend on the conversion technology. For instance, the Carbo-Consult CCE-SJG Gasifier (Eckermann, 2009) discussed in Von Doderer (2009) has a throat diameter of approximately 22cm, allowing chunks of up to 22cm to be fed into the system. The particle size requirements for conversion also play an important role in productivity, cost-effectiveness and emissions from the comminution process (see also Van Belle, 2006).

The quality of fuelwood affects costs and productivity in several ways. Contaminants, such as stones, metal and sand, can damage chipper blades, which then require more frequent replacement or sharpening. Dull blades impair chipper productivity and result in an undesirable chip size. Dry residues increase costs by 10-20%, and the presence of contaminants raises the costs even more (Richardson et al., 2002: 137).

4.3.1.4 Biomass pretreatment: drying

Thermal pretreatment, i.e. the drying of biomass, represents an essential step toward turning green biomass into electricity, and is linked to the storage conditions thereof. As discussed in section 2.4.4, the moisture stored in biomass has a direct effect on the calorific value of the fuelwood, i.e. the drier the biomass, the higher the calorific value. However, drying does not seriously affect the volume of woody biomass (Hamelinck et al., 2005: 122). Fuelwood is stored either uncomminuted or in comminuted form.

Biomass produced in an SRC production system can be stored in the field, at the roadside, at a terminal, and/or at the landing of the central conversion plant. The rate of transpiration or ‘air-drying’ depends on many factors, including ambient temperature, relative humidity, wind speed, season, rainfall pattern, tree species, and tree size. The best season for drying is when the vapour pressure deficit of the ambient air is low (Richardson et al., 2002: 108). Additionally, the in-field storage of biomass in small heaps allows the foliage to remain in the plantation, resulting in reduced nutrient loss and better fuel quality. Usually, transpiration, or air-drying, is more efficient in small heaps than in roadside windrows. The weight losses associated with fungal decay are smaller when stored in windrows than when stored as chipped material. Heat development, a problem with chip storage, is also eliminated (Richardson et al., 2002: 110).

4.3.1.5 Biomass upgrading: mobile fast-pyrolysis

A significant portion of biomass feedstock costs can be attributed to the ‘handling’ associated with its movement from the point of production to the point of conversion and end use (Sokhansanj, 2002). Traditionally, handling includes harvesting, chipping, and loading of the biomass onto trucks, and transporting it to end-use points. Additionally, handling includes the operations at the end-use point, including weighing, dumping, screening, grinding, storage, various conveying operations, and metering into the end-use system (Badger and Fransham, 2006: 321). Handling solid forms of biomass is expensive for a number of reasons, including the number of operations required and the low bulk density of the feedstocks (Badger, 2002). If raw biomass could be densified into liquid (e.g. bio-oil) and/or into solids (e.g. bio-char) it would simplify the handling, transportation, storage, and usage of the feedstock. Additionally, bio-oil and bio-char have a much greater energy density than raw biomass. The process capable of achieving this is fast pyrolysis.

Pyrolysis is one of the important thermo-chemical conversion processes. It is carried out either in the complete absence of oxygen or with a limited supply of it. When significantly less oxygen is present than required for complete combustion, pyrolysis can convert the biomass into usable high energy content products such as pyrolysis oil (also referred to as bio-oil), bio-char, and bio-gas. The relative proportions of oil, char, and gas depend significantly on the pyrolysis method employed and the characteristics of the biomass, as well as on reaction time and temperature (Kumar et al., 2010). For a more detailed discussion of pyrolysis principles, types and product properties, refer to section 4.3.1.7, 5.3.4 and 5.3.5.

The mobile fast pyrolysis process that is proposed for a number of bioenergy alternatives encompasses the installation of a modular and transportable conversion plant, allowing it to be located close to the source of the biomass (e.g. at the roadside), and the subsequent transportation of high-energy and dense bio-oil and bio-char to a central conversion plant. This is particularly appealing for remote areas characterised by a lack of infrastructure and long transportation distances.

4.3.1.6 Secondary transport

For environmental and economic reasons, biomass for energy conversion is usually considered to be a local resource (Forsberg, 2000: 18). This is due to the large areas of land required to produce and source biomass, resulting in the development of harvesting systems and transportation networks, leading to the increase in costs and greenhouse gas emissions associated with producing biomass on large areas of land. Evidently, an optimum must be reached between economy of scale of the conversion plant and the variable associated transportation costs (Schlamadinger et al., 2006: 2).

The term 'secondary transport' refers to the movement of timber, woody biomass or other related products, from the primary landing to the processing plant. This may be accomplished by a single mode of transport using a vehicle, or it may encompass a number of modes of transport (road, rail, and water) and many vehicles (Morkel, 2000: 382). Given the local circumstances in the CWDM, road transport appears to be the most viable option (Roberts, 2009: 28). Research by Van Dam et al. (2009) has also shown that transporting biomass over a short distance (taken to be less than 100km) using trucks is the preferred option, especially where multiple sites have to be visited, and also where rail and waterway infrastructures do not exist.

Wood transportation from a forest landing to forest-based industries uses large amounts of energy. In the case of Sweden, where forest operations are highly and efficiently mechanised, this stage consumes more fossil fuels than other elements of the wood supply chain (such as silviculture and logging operations) (González-García et al., 2009: 3530).

Important guiding principles and decision-making guidelines on appropriate vehicles for forestry and bioenergy applications exist, and these can be summarised for the relevant application (an appropriate vehicle is one that is specifically matched to a defined application), legislation of the specific country, and cost efficiency (Krieg, 2000: 388). Additionally, when deciding on the appropriate truck configuration, global technological developments need to be considered (Webster, 2000). This is a function of several factors, namely, the type and volume of commodity to be transported; the terrain conditions, and their influence on road width and curvature; the gravel-to-paved surface ratio; the back-haul requirements; as well as the number of demand points, their locations, and product requirements (Brink and Krieg, 2000: 378).

Four main features are typical for commercial road haulage (Rogers and Brammer, 2009: 1368), namely, the high annual distance covered by each truck; the low proportion of time spent for loading and unloading; the loads achieved between different destinations, in order to reduce unloaded travel time; and the large proportion of journeys on motorways and major trunk roads. In contrast, given the nature of bioenergy systems, fleets of trucks shuttling between biomass plantations and conversion plants are required. A much greater proportion of time is spent on loading and unloading, as well as on travelling on slower, rural roads. Consequently, their cost structure will vary from those of commercial freight haulers (Rogers and Brammer, 2009).

Especially in forestry or bioenergy applications, truck power requirements are regarded as a crucial factor, since long periods of time are spent transporting heavy loads across gravel and dirt roads in mountainous terrain, as is commonly found in the CWDM. Hence, the truck used in this environment requires greater power and torque than, for instance, that used for long-distance transportation on good roads (Roberts, 2009: 30).

Besides fulfilling power and torque requirements, when selecting the appropriate truck, great attention should be given to the feedstock itself. Woody biomass is characterised, *inter alia,* by its low bulk density, often limiting the load by volume rather than by mass capacity. The economy of scale in transporting low bulk material invariably dictates that the load must either be compacted or the load space extended. In practice, the load space must be built according to the maximum allowable dimensions. Nevertheless, in many cases, the maximum allowable weight will not be achieved. The load extension may also have to be adjusted for some locations where access to the raw material is restricted by low-quality roads (Ranta and Rinne, 2006: 231).

The transporter capacity is expressed in terms of the mass to be transported:

Equation 5: Transport capacity

$$W_b = k\rho_b V$$

Where W_b is the wet mass of biomass (t), ρ_b the wet bulk density of biomass (t/m^3), V the volume capacity of the pole-trailer/container-trailer (m^3), and the coefficient k represents less than maximum payload scenarios.

Furthermore, in order to determine the effective transport rate, the total transport time per load needs to be established. For the total transport time per load, three aspects are of importance, namely, loading time, travelling time, and unloading time (Roberts, 2009: 28).

Equation 6: Total transportation time per load

$$t_{tr} \frac{(t_{fwd} + t_{return} + t_{load} + t_{unload})}{E_t}$$

Where t_{tr} represents the total transportation time per load (h), t_{fwd} the forwarding time per load, t_{return} the return time per load, t_{load} the loading time per load, t_{unload} the unloading time per load, and E_t the efficiency factor for the transport equipment due to obstacles that may increase transportation time (<1).

The effective transport rate (W_t) is a function of the actual mass of the commodity to be transported (W_b) and the total transportation time per load (t_{tr}), and can be calculated as follows:

Equation 7: Effective transport rate

$$W_t = W_b/t_{tr}$$

W_t stands for the rate of mass transport (wet t/h), W_b for the wet mass of biomass (t/m3), and t_{tr} for the total transport time per load (h). W_b has a maximum value based on the weight limit of the road. In other words, if $W_b$exceeds the legal limits, then V or k has to be reduced (Sokhansanj et al., 2006: 843).

Following the production steps prior to secondary transport, six types of bioenergy feedstocks are to be transported to a central conversion facility. They can be categorised as uncomminuted or comminuted biomass, and as mobile fast-pyrolysis products:

- Uncomminuted biomass:
  - Whole tree including branches and top
  - Logs/stemwood (motor-manual harvesting with manual loading and unloading)
- Comminuted biomass
  - Whole tree including branches and top
  - Logs/stemwood
- Mobile fast pyrolysis
  - Bio-oil
  - Bio-char

Table 13, below, shows the bulk densities for various types of woody biomass feedstock in relation to different moisture content levels, as determined by De Wet (2010). As is commonly accepted in industry, an average moisture content of 40% (dry basis) for the biomass is assumed for secondary transport (De Wet, 2010; Ranta and Rinne, 2006). The exception to this is the one-pass harvesting method, where the trees are felled and comminuted in a single operation. In this case, a moisture content of 80% is assumed.

Table 13: Bulk densities of biomass at various levels of moisture content

Moisture content (%, dry basis)	0%	20%	40%	60%	80%
	Bulk density (t/m^3)				
Whole tree/utilisable biomass (incl. bark, branches, etc.)	0.14	0.17	0.2	0.23	0.31
Log/stemwood	0.48	0.57	0.67	0.77	1.03
Comminuted biomass from whole tree	0.24	0.28	0.33	0.37	0.51
Comminuted biomass from log/stemwood	0.29	0.34	0.40	0.46	0.62

Note:

Transport bulk density is generally assumed to be 40% moisture content for dry matter, except for the one-pass harvesting method, where a bulk density of 0.51t/m^3 (80% MC) is assumed. Other bulk density levels are extrapolated from data provided by (De Wet, 2010).

It should be noted, however, that further research is required to validate the above-mentioned bulk densities for the different woody biomass types. In Finland, for instance, Ranta and Rinne (2006) assume a bulk density for chipped biomass from logging residues of 0.36-0.46t/m^3, but 0.15-0.20t/m^3 for uncomminuted logging residues.

4.3.1.7 Bio-energy generation

The exploration of alternative energy sources, particularly renewable energy sources, is driven, in part, by the negative environmental impact and limited supply of conventional, non-renewable fossil fuels (DeSisto et al., 2010: 2642). Bioenergy is a renewable and clean energy source that is derived from biomass.

The conversion routes for producing energy carriers from biomass are plentiful (Faaij, 2006: 345). Figure 13 illustrates the main conversion routes that are used or are under development for producing heat, power, and transport fuels. While biological processing using biological catalysts is usually very selective and produces a small number of discrete products with high yields, thermal conversion with inorganic catalysts often gives multiple and complex products over very short reaction times, and is often used to improve the product quality or spectrum (Bridgwater, 2011: 1; Czernik and Bridgewater, 2004).

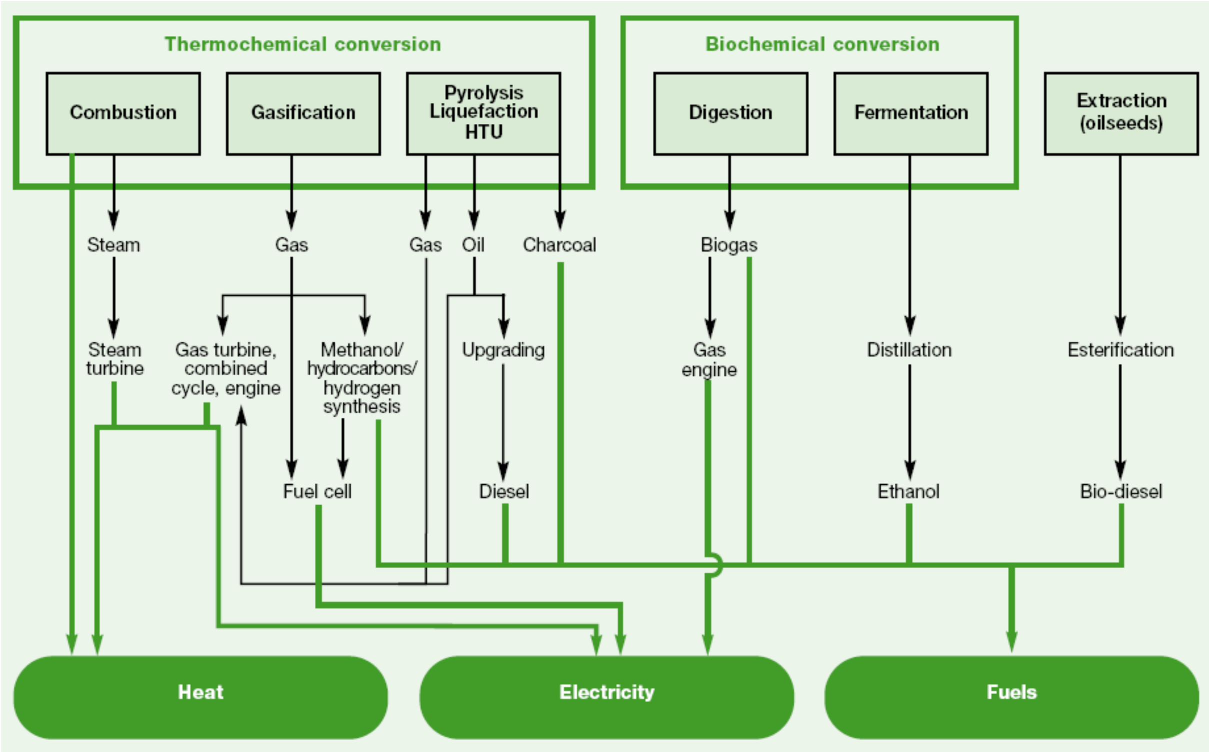

Figure 13: Main conversion options for biomass to secondary energy carriers

Source: Turkenburg et al. (2000: 223)

Among the options for renewable energy production, the thermal conversion of biomass is receiving considerable attention (Bridgwater et al., 1999; Oasmaa et al., 2010; DeSisto et al., 2010).

This study focuses solely on the thermo-chemical conversion processes available for converting biomass to a more useful energy form, namely, combustion, gasification and pyrolysis, since electrical energy is the main product desired when using lignocellulosic biomass as a feedstock. Figure 14, below, summarises the markets for the products of these processes. Their relationships to one another and their oxygen requirements are summarised in Figure 15, below.

Combustion is a well-established commercial technology with applications in most industrialised and developing countries, and associated development is concentrated on resolving environmental problems (Koppejan and van Loo, 2009). Gasification has been practiced for many years, and while there are many examples of demonstration and pre-commercial activities, there are still surprisingly few successful commercially operational units (Bridgwater, 2011: 1). Fast pyrolysis is an advanced emerging technology representing either an integrated process for producing a liquid fuel that can be used directly, or an intermediate pretreatment step for converting solid biomass into a form of higher-energy-content transportable liquid for subsequent processing to be converted to heat, power, biofuels, and chemicals (Bridgwater, 2011: 1).

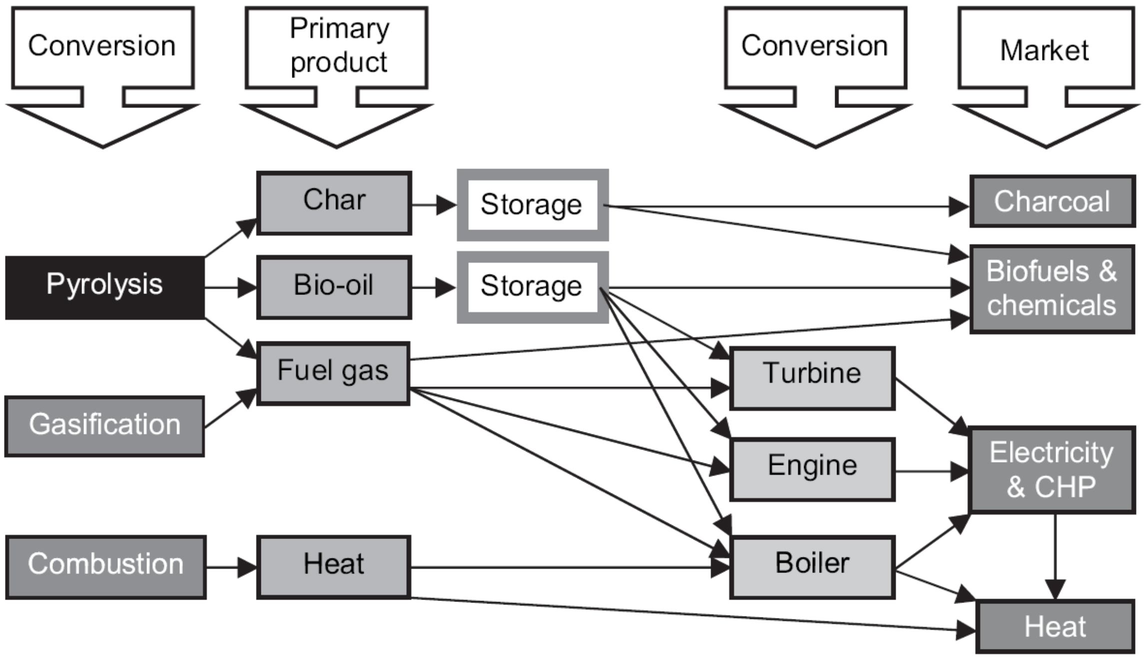

Figure 14: Products from thermal biomass conversion

Source: Bridgwater (2011: 2)

When analysing bioenergy systems, it should be borne in mind that the different conversion technologies in the process of generating energy, the different fuels, and the different forms of fuel processing result in varying environmental effects. The chief characteristics of conversion technologies are the following (Jungmeier et al., 2003: 102):

- Conversion efficiency from fuel to electricity and/or heat (η_{el}, η_{th}),
- Ratio of electricity to heat ($\alpha = \eta_{el}/\eta_{th}$),
- Emissions to air (flue gas cleaning system), and
- Ash treatment.

Generally, great emphasis is given to the first characteristic. However, not only the final energy-carrier-to-electricity-efficiency ratio is important, but also the conversion efficiency of the pretreatment steps prior to the final conversion, e.g. when converting biomass into pyrolysis products, etc. All conversion and pretreatment steps influence the overall biomass-to-energy efficiency ratio, and therefore, the mass balance of each particular system, resulting in the amount of land required to supply sufficient biomass to ensure the continuous generation of five megawatts of electricity in 7 920 hours per year (refer to section 4.2).

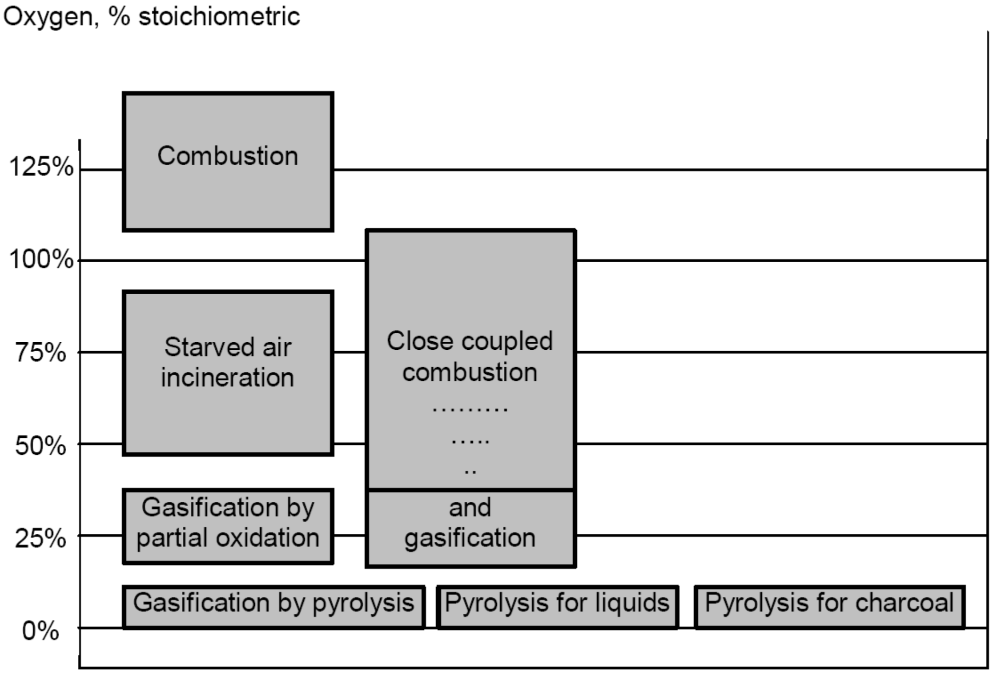

Figure 15: Thermal conversion processes

Source: Bridgwater (2002: 2)

- **Combustion**

Combustion is the most widely used process for biomass conversion. It accounts for over 97% of bioenergy production in the world. In some less-developed countries, combustion of traditional biomass plays an important role in people's lives, as it is the main source of energy available for cooking and heating. Regarded as a proven low-cost, but highly reliable technology, combustion is relatively well understood and commercially available (Demirbas and Demirbas, 2007; IEA, 2002). The product is heat, which must be used immediately to heat and/or generate power, as storage is not a viable option.

Production of heat (domestic and industrial) and electricity, or combined heat and power (CHP), is possible through a portfolio of options. The larger-scale combustion of biomass for the production of electricity (as well as heat and process steam) is undertaken commercially worldwide. Many plant configurations have been developed and deployed over time. Basic combustion concepts include pile burning, various types of grate firing (stationary, moving, vibrating), suspension firing, and fluidised bed concepts (Faaij, 2006).

As mentioned in section 2.4, in comparison with fossil fuels, biomass fuels have relatively low heating values. This can be explained by two of their distinct characteristics: high moisture and high oxygen content. The high moisture content is one of the most significantly disadvantageous features of using biomass as a fuel. Although the combustion reactions are exothermic, the evaporation of water is endothermic. To maintain a self-supporting combustion process, the moisture content (on a wet basis) of biomass fuels cannot be higher than 65% (Jenkins et al., 1998: 37). In addition, the heating value of the fuel is negatively correlated with the relative moisture content, even when this is within the maximum acceptable limit (Zhang et al., 2010: 971; Demirbas, 2004).

Biomass combustion is a complex process consisting of consecutive homogeneous and heterogeneous reactions, which can be subdivided in three main stages: drying; pyrolysis and reduction; and combustion of volatile gases and solid char (IEA, 2002). Figure 16 gives a schematic description of these processes for wood. The composition and physico-chemical properties of the fuel are the determining factors for the duration and rate of each step of the process (Khan et al., 2009). The combustion of volatile gases contributes more than 70% of overall heat generation. This takes place above the fuel bed and is generally evident from the presence of yellow flames. Char is combusted in the fuel bed and is evident from the presence of small blue flames (Zhang et al., 2010; Quaak et al., 1999; IEA, 2002). The combustion of biomass on a large scale is still considered to be a complex process with technical challenges associated with the biomass fuel characteristics, types of combustors, and the co-firing processes.

The overall efficiencies of converting biomass to power tend to be rather low due to the process' inherent natures (i.e. the fundamental thermodynamic limitations associated with their operating pressures and temperatures (Envergent Technologies, 2010), which are typically 15% for very small plants and up to 35% for larger and newer plants. However, existing technologies are widely available commercially, and there are many successful working examples throughout North America and Europe that frequently utilise forestry, agricultural, and industrial wastes. Emissions and ash handling remain technical problems though (Bridgwater, 2002).

The co-combustion of biomass, particularly in coal-fired power plants, offers several advantages: the overall efficiency is high (usually around 40%) due to the economies of scale of the existing plant, and investment costs are negligible when high-quality fuels such as pellets are used. Also, directly avoided emissions are high due to the direct replacement of coal. Co-firing combined with the fact that many coal-fired power plants in operation are fully depreciated usually makes it a very attractive GHG mitigation option. In addition, biomass firing leads to the lowering of sulphur and other emissions (Faaij, 2006). The most utilised combustors for biomass applications are stoker-fired and fluidised bed designs, with the latter rapidly becoming the preferred technology because of the low amount of NO_x emissions (Caputo et al., 2005).

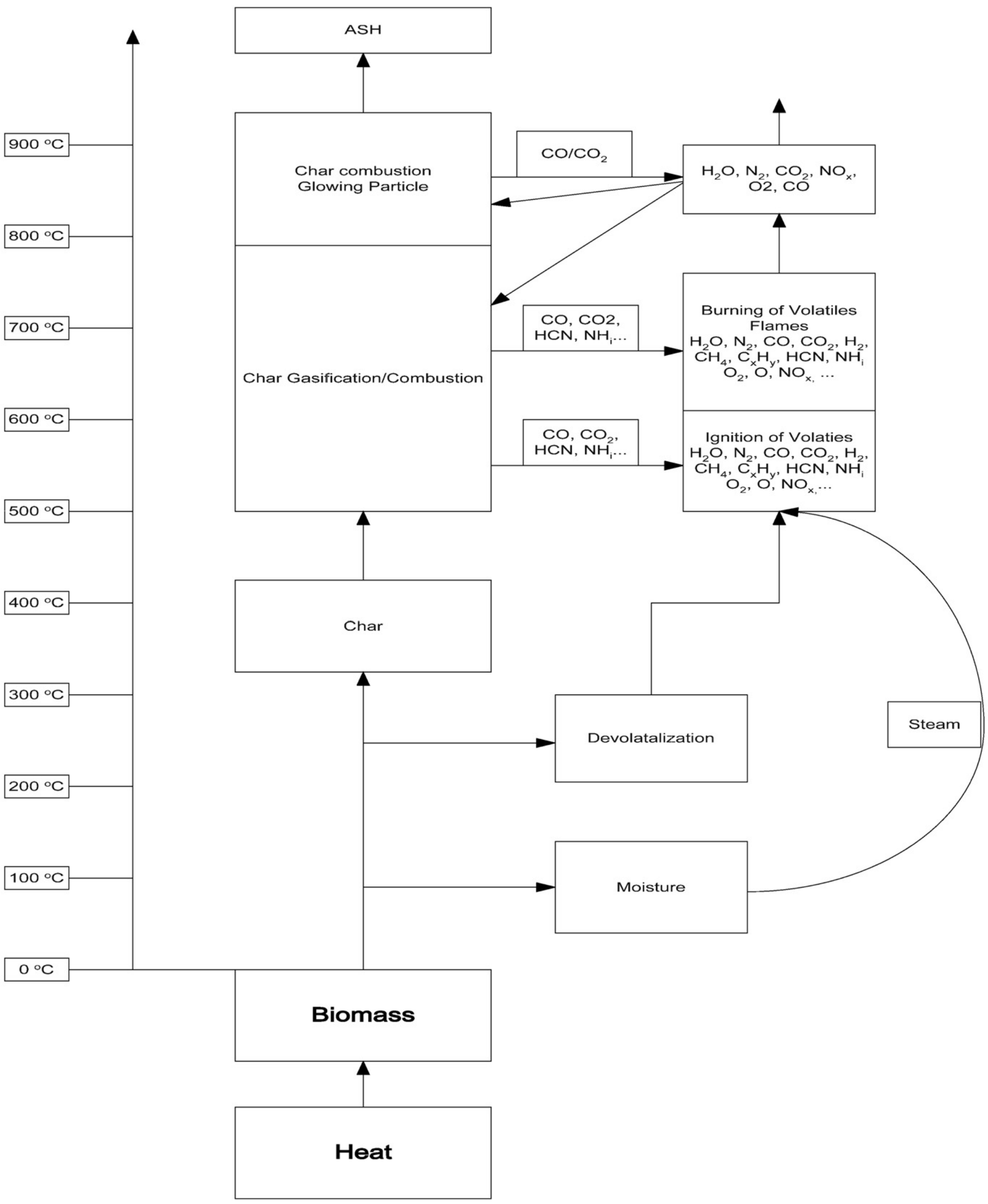

Figure 16: Schematic description of the process of combusting a wood chip

Source: Khan et al. (2009: 29)

- **Gasification**

Gasification converts biomass through partial oxidation into a gaseous mixture of syngas, consisting of hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and carbon dioxide (CO_2) (Knoef, 2005; Higman and van der Burgt, 2003). The oxidant or gasifying agent can be air, pure O_2, steam, CO_2, or a combination thereof (Wang et al., 2008: 574). The gas can be burned directly for cooking or heating purposes, or can be used in internal combustion engines or gas turbines for producing electricity or shaft power (Abdul Salam and Bhattacharya, 2006: 228). Figure 17, below, shows a schematic illustration of the processes involved in biomass gasification.

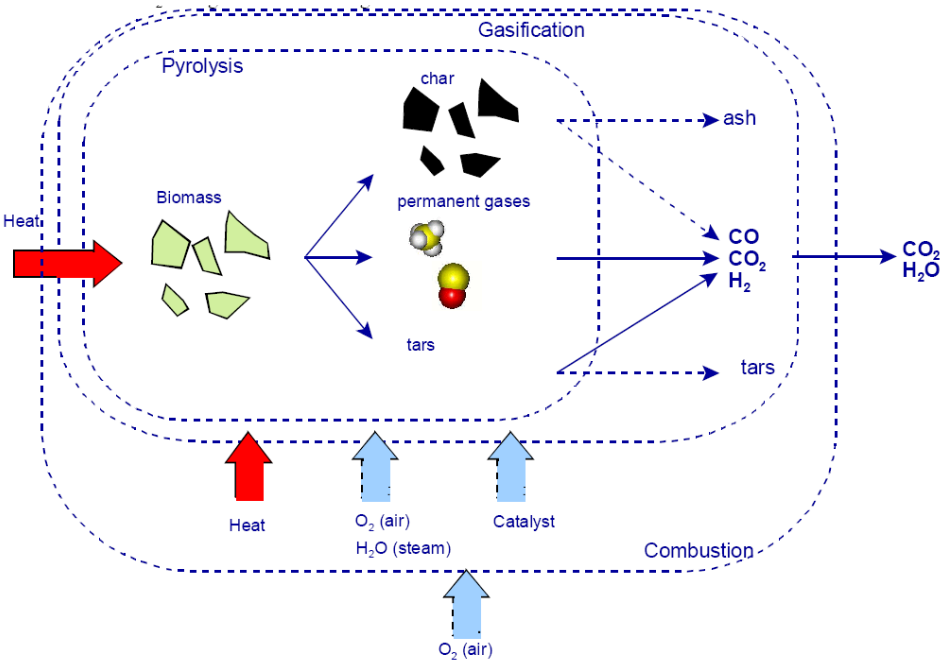

Figure 17: Schematic illustration of gasification as one of the thermal conversion processes

Source: Swaaij et al. (2002: 1)

There are three main types of gasifiers: fixed-bed, moving-bed and fluidised-bed (Knoef, 2005; Higman and van der Burgt, 2003; Basu, 2006). Both fixed-bed and moving-bed gasifiers produce syngas, with large quantities of either tar and/or char, due to the low and non-uniform heat and mass transfer between the solid biomass and the gasifying agent (Wang et al., 2008: 574). Both are simple and reliable designs and can be used to economically gasify very wet biomass on a small scale (Basu, 2006). Fluidised-bed gasifiers, which consist of a large percentage of hot inert bed materials such as sand and 1-3% biomass have been used widely in biomass gasification (Basu, 2006). Fluidised bed gasification can achieve a high heating rate, uniform heating and high productivity (Van der Drift et al., 2001). Although not common, entrained bed reactors, e.g. cyclone reactors, have also been used for biomass gasification. The performance of a gasifier depends on the design of the gasifier, the type of fuel used and the airflow rate, among others (Abdul Salam and Bhattacharya, 2006).

As illustrated in Figure 17, when aiming at generating thermal and/or electrical energy, the syngas can be used either in a combustor or directly fed to gas engines. Compared with direct biomass combustion, the syngas from biomass gasification can increase the bio-based fuel percentage in existing pulverised coal combustors, without posing any concern about the plugging of the coal-feeding system during the co-firing of biomass coal (Wang et al., 2008). Biomass gasification can reduce the potential of ash slugging or other ash-related problems, because the gasification temperature is lower than combustion and clean syngas is supplied to the combustor. Furthermore, a gasification process can use a variety of biomasses with large variations in their properties, such as moisture content and particle size (Raskin et al., 2001). However, if syngas is combusted directly to generate steam for generating power via a steam turbine, the electricity efficiency is limited by the theoretical limit of a steam turbine.

High-quality syngas with almost no tar and dust, and a high heating value can be fed to gas engines directly (Wander et al., 2004; Sridhar et al., 2001) or to gas turbines (Gabra et al., 2001a; Rodrigues et al., 2003; Gabra et al., 2001b; Miccio, 1999) to generate power. Gas turbines can transform hot syngas into mechanical energy and thus increase the energy efficiency of conversion. A typical ‘biomass-integrated gasification combined-cycle’ (BIGCC) involves combustion of the hot syngas from a gasifier in a gas turbine to generate electricity in a topping cycle (Wang et al., 2008). The hot exhaust gas from the turbine is used to generate steam through a heat-recovery steam generator (Rodrigues et al., 2003; Carpentieri et al., 2005). The steam is used in a steam turbine to generate additional electricity in a bottom cycle, or is used as processing heat.

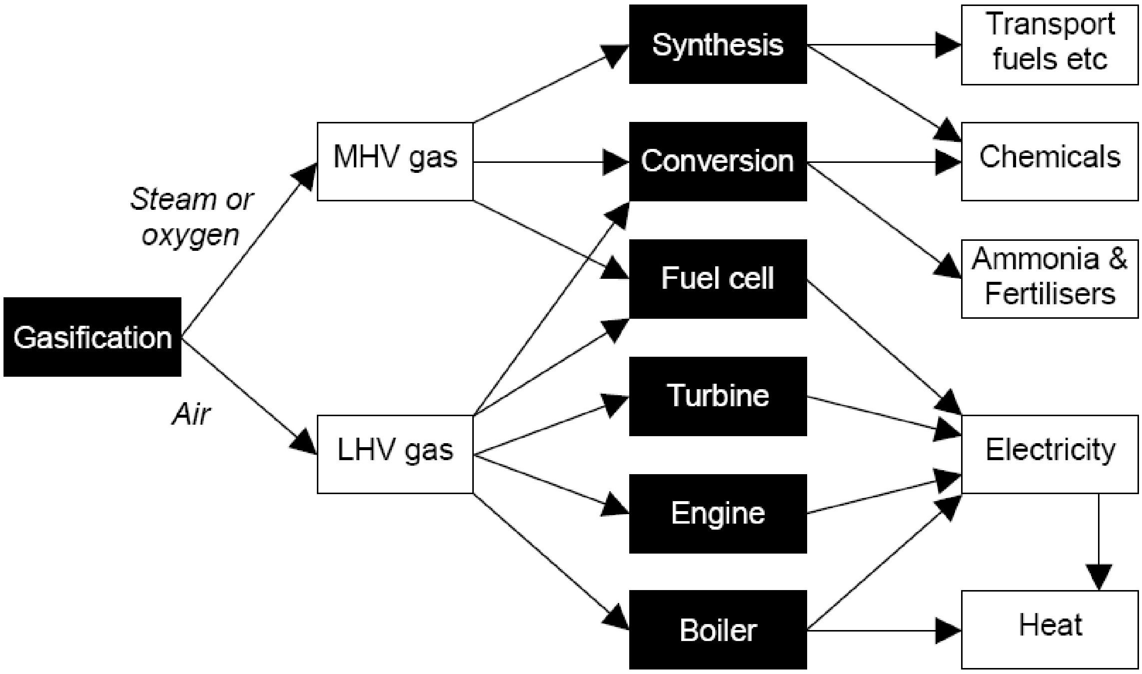

Figure 18: Applications for gas from biomass gasification

Source: Bridgwater (2002: 10)

Further information and literature on the thermal gasification of biomass is abundant – *inter alia,* refer to Abdul Salam and Bhattacharya, 2006; Basu, 2006; Bridgwater et al., 2002; Caputo et al., 2005; Klass, 1998; Clini et al., 2008; Cummer and Brown, 2002; Demirbas, 2009a; Di Blasi, 2009;

Faaij et al., 1997; Francisco V. Tinaut, 2008; Gabra et al., 2001a; Gabra et al., 2001b; Gil et al., 1999; Higman and van der Burgt, 2003; Mamphweli and Meyer, 2009; McKendry, 2002b; Melchior et al., 2009; Miccio, 1999; Persson, 2009; Quaak et al., 1999; Querleu, 2009; Rezaiyan and Cheremisinoff, 2005; Sandvig et al., 2003; Turn et al., 2005; Wander et al., 2004; and Wang et al., 2008.

- **Pyrolysis**

Pyrolysis has been applied for thousands of years to produce charcoal. In this conventional, or slow-wood, pyrolysis process, biomass is heated slowly (at a heating rate of 5-7°C/min) up to 500°C, where the vapour residence time varies from 5 to 30 minutes (Bridgwater et al., 2001). Vapours do not escape as rapidly as they do during fast pyrolysis. Thus, components in the vapour phase continue to react with each other, resulting in more char formation. It is only during the last 30 years that fast pyrolysis at moderate temperatures of around 500°C and very short reaction times of up to two seconds has gained in appeal and application. This is because the process gives direct high yields of liquids of up to 75 weight percent (wt.%), which can be used directly in a variety of applications (Czernik and Bridgewater, 2004), or as an efficient energy carrier (Bridgwater, 2011). Hence, it has advantages for energy efficiency, because mainly liquid fuels and solid char are formed, both of which are easy to store and transport (Van de Velden et al., 2008).

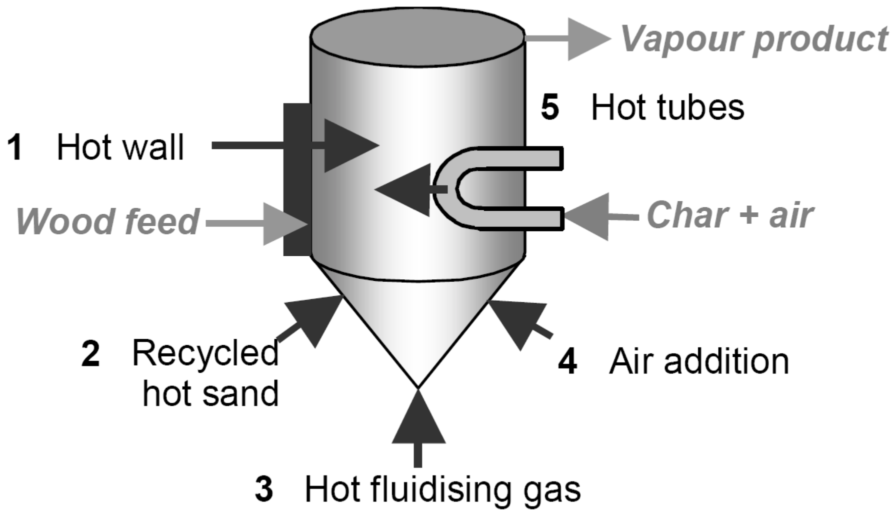

Figure 19: Methods of heat transfer to a pyrolysis reactor

Source: Bridgwater (2002: 11)

The production of the liquid fraction of bio-oil is receiving growing interest. This is because its use is especially advantageous when biomass resources are remote from where the energy is required or where the specific technology is located, since the liquid can be stored or transported more easily than solid heterogeneous feedstock. In this way, it is possible to decouple liquid fuel production from its utilisation, separate the minerals inherently present from the minerals at the site where the liquid fuel is produced, transport the bio-oil to bio-refineries for its upgrading to obtain transportation fuels and valuable chemicals, or to transport it to large power plants to convert it into heat and power (Cherubini, 2010).

Pyrolysis is thermal decomposition in the complete absence of an oxidising agent (air or oxygen), or with such a limited supply of the oxidising agent that combustion or gasification does not occur to an appreciable extent. Pyrolytic cracking of biomass yields mainly liquids, together with a solid residue (char) and gas. In comparison to gasification, pyrolysis occurs at relatively low temperatures (300-600°C) (Van de Velden et al., 2008). Lower process temperatures and longer vapour residence times favour the production of charcoal. High temperatures and longer residence times increase biomass conversion to gas, while moderate temperatures and a short vapour residence time are optimum for producing liquids. Three products are always produced, but the proportions can be varied over a wide range by adjusting the parameters of the process (Bridgwater, 2011). These essential parameters include (Van de Velden et al., 2008; Bridgwater, 2011):

- Very high heating rates and high heat transfer at the biomass particle reaction surface usually require a finely ground biomass feed of typically less than 3mm, as biomass generally has low thermal conductivity;
- Carefully controlled pyrolysis reaction temperatures around 500°C to maximise the liquid yield for most biomass, and temperatures for the vapour phase of 400-500°C;
- Short, hot vapour residence times of typically less than two seconds to minimise secondary reactions;
- Fast char separation to avoid secondary cracking, and
- Rapid cooling of the pyrolysis vapours.

In addition to the above-mentioned essential parameters, feedstock properties – such as moisture content or particle size – as well as its feed rate, and the process used for fast pyrolysis of the biomass influence pyrolysis product yields and the properties thereof. In general, higher temperatures and longer residence times maximise gas formation, and minimise char formation (Bridgwater et al., 1999; DeSisto et al., 2010). Because of the complexity of the process, reactor types and feedstock variation, the effect of operating conditions on the bio-oil properties is very process specific (DeSisto et al., 2010). The relative proportions depend on the pyrolysis method, the characteristics of the biomass, and the reaction temperature (Amutio et al., 2011; Kumar et al., 2010; Demirbas, 2009a).

Table 14 indicates the product distribution obtained from different modes of pyrolysis, showing the considerable flexibility achievable by changing process conditions.

Table 14: Typical product weight yields obtained by different methods for pyrolysing wood

Mode	**Conditions**	**Product yield (wt.%, dry basis)**		
		Liquid	**Solid**	**Gas**
Fast	~500°C, short hot vapour residence time: ~1s	75%	12% char	13%
Intermediate	~500°C, hot vapour residence time: ~10-30s	50% in two phases	25% char	25%
Carbonisation (slow)	~400°C, long vapour residence time: hours→days	30%	35% char	35%
Gasification	~750-900°C	5%	10% char	85%
Torrefaction	~290°C,solids residence time ~10-60min	0%, unless condensed, then up to 5 %	80% solid	20%

Source: Bridgwater (2011: 2)

The main product of fast pyrolysis, bio-oil, is obtained in yields of up to 75wt.% on a dry-feed basis, together with the by-products char and gas, which can be used within the process to provide the process' heat requirements, so there are no waste streams other than flue gas and ash. The liquid yield depends on biomass type, temperature, hot vapour residence time, char separation, and biomass ash content, with the last two having a catalytic effect on vapour cracking (Bridgwater, 2011: 3). The pyrolysis process itself requires about 15% of the energy in the feed. The gas has a medium heating value and can be used internally to provide process heat, recirculated as an inert carrier gas, or exported, for example, for feed drying (Cottam, 1995).

A fast pyrolysis process includes drying the feed to typically less than 10% water in order to minimise the water in the product liquid oil, grinding the feed to give sufficiently small particles to ensure rapid reaction, fast pyrolysis, rapidly and efficiently separating solids (bio-char), and rapidly quenching and collecting the liquid product (bio-oil) (Bridgwater, 2011: 3).

Virtually any form of biomass can be considered for fast pyrolysis. Nonetheless, most work has been carried out on wood because of its consistency and comparability for testing – over 100 different biomass types have been tested by many laboratories, ranging from agricultural wastes such as straw, olive pits and nut shells to energy crops such as miscanthus and sorghum, forestry residues such as bark, and solid wastes such as sewage sludge and leather wastes (Bridgwater, 2011: 3).

At the heart of a fast pyrolysis process is the reactor. Although it probably represents only 10-15% of the total capital costs of an integrated system, most research and development has focused on developing and testing different reactor configurations on a variety of feedstocks. However, increasing attention is now being paid to controlling and improving liquid quality, and improving liquid collection systems (Bridgwater, 2011: 3). The rest of the fast pyrolysis process comprises biomass reception, storage, handling, drying and grinding; and product collection, storage, and when relevant, upgrading.

Different fast pyrolysis types are available, such as bubbling fluid bed reactor systems, circulating fluid bed and transported bed reactor systems, rotating cone reactor systems, and ablative pyrolysis systems. Several comprehensive reviews of fast pyrolysis processes for liquid production are available, such as Mohan et al. (2006a), Kersten et al. (2005), and Bridgwater (2002, 2003, 2011).

As illustrated in Figure 10, above, where bioenergy alternatives encompass mobile or centralised stationary pyrolysis, bio-oil and bio-char are the utilisable products for further conversion into electricity. Hence, a more detailed description of these pyrolysis products follows.

Pyrolysis liquid is referred to by many names, including pyrolysis oil, bio-oil, bio-crude-oil, bio-fuel-oil, wood liquids, wood oil, liquid smoke, wood distillates, pyroligneous tar, pyroligneous acid, and liquid wood. The crude pyrolysis liquid is typically almost black through to dark red-brown, and approximates to the original feedstock in its elemental composition (refer also to Table 15, below). It is composed of a very complex mixture of oxygenated hydrocarbons and water (Bridgwater, 2002). Water is obtained from the original moisture in the feedstock (typically about 12wt.%, dry basis) and from the dehydration reactions occurring during pyrolysis, ranging from 15wt.% to an upper limit of about 30-50 wt.%, depending on the feed material and how it was produced and subsequently collected. The water yield increases slightly when the temperature is increased, as a result of the increase in the secondary cracking-dehydration reactions (Amutio et al., 2011), resulting in a total of around 25 wt.% moisture content. Solid char and dissolved alkali metals from ash may also be present (Huffman et al., 1993).

The liquid is formed by rapidly quenching and thus ‘freezing’ the intermediate products of the flash degradation of hemicellulose, cellulose, and lignin. The liquid thus contains many reactive species, which contribute to its unusual attributes (Bridgwater, 2011: 10). Bio-oil can be considered a micro-emulsion in which the continuous phase of an aqueous solution of holocellulose decomposition products stabilises the discontinuous phase of pyrolytic lignin macromolecules through mechanisms such as hydrogen bonding. Aging or instability is believed to result from a breakdown in this emulsion. In some ways bio-oil could be considered analogous to the asphaltenes found in petroleum (Bridgwater, 2002: 16).

Table 15: The range of elemental composition and properties of wood-derived pyrolysis oils

Physical properties		
Water content (wt%)		15-30
pH		2.8-3.8
Density (kg/m3)		1500-1250
Elemental analysis (wt%, moisture free)	C	55-65
	H	5-7
	N	0.1-0.4
	S	0.00-0.05
	O	Balance
	Ash	0.01-0.30
HHV (MJ/kg)		16-19
Viscosity (315K, cP)		25-1000
ASTM vacuum distillation (wt%)	430 K	~10
	466 K	~20
	492 K	~40
	Distillate	~50

Pyrolysis conditions	
Temperature (K)	750-825
Gas residence time (s)	0.5-2
Particle size (μm)	200-2000
Moisture content (wt%)	2-12
Cellulose (wt%)	45-55
Ash (wt %)	0.5-3
Yields (wt.%, dry basis)	
Organic liquid	60-75
Water	10-15
Char	10-15
Gas	10-20
Solubility (wt%)	
Hexane	~1
Toluene	15-20
Acetone	>95
Acetic acid	>95

Source: Venderbosch and Prins (2010: 182)

Assuming typical feed material, with a specification of a maximum of 10% moisture in the dried feed material, fast pyrolysis oil has a HHV of about 17MJ/kg (compared with 43-46MJ/kg for conventional fuel oils), and is produced with about 25wt.% water, which cannot readily be separated. While the liquid is widely referred to as 'bio-oil', it will not mix with any hydrocarbon liquids due to its high oxygen content of 35-40wt.%, which is similar to that of biomass. It is composed of a complex mixture of oxygenated compounds comprising more than 230 organic chemicals (Kumar et al., 2010: 163), which provide both the potential and the challenge for utilisation (Bridgwater, 2011). The density of the liquid is about 1 200kg/m^3, which is higher than that of light fuel oil (around 850kg/m^3) and significantly higher than that of the original biomass (Demirbas, 2009b). This means that bio-oil has about 42% of the energy content of fuel oil on a weight basis, but 61% on a volumetric basis.

Table 16: Pyrolysis oil yields for various feeds

Biomass feedstock type	Typical pyrolysis oil yield (wt.%, dry basis)
Hardwood	70-75
Hardwood bark	60-65
Softwood	70-80
Softwood bark	55-65
Corn fibre	65-75
Bagasse	70-75
Waste paper	60-80

Source: Streff (2010)

Table 16 presents some typical bio-oil yields for a variety of biomass feedstock types. Below, Figure 20 shows some possible applications of pyrolysis oil. However, while pyrolysis oil can be upgraded to transport fuels or other usable chemicals, this study focuses solely on its application for the generation of electricity, with thermal energy as a by-product.

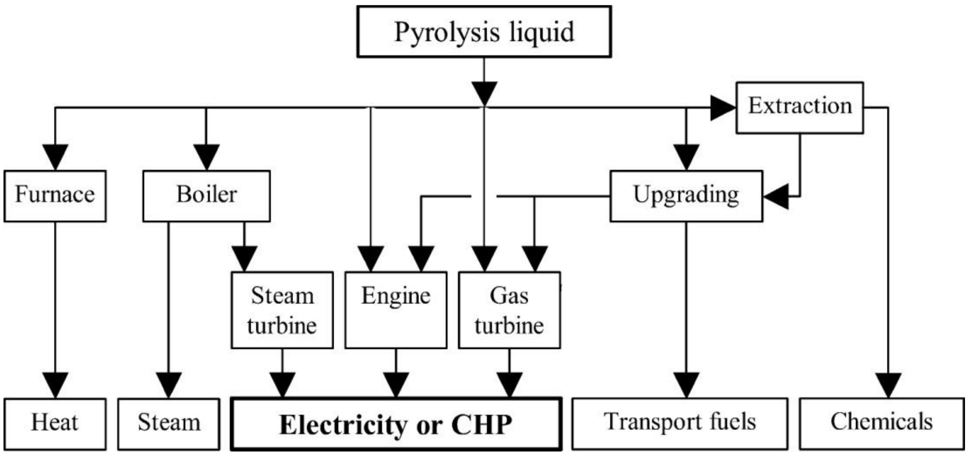

Figure 20: Fast pyrolysis applications

Source: Bridgwater et al. (2002: 187)

Findings by Venderbosch et al. (2010) indicate that bio-oil could, for the time being, be used to substitute fossil fuels in heat and power production, through combustion in conventional boilers or co-combustion in power stations. Over the next few years, the focus will be on producing oil and on applying simple and cheap applications. As the technology advances, larger amounts of oil will become available for the development and commercial-scale demonstration of other bio-oil applications, such as turbines or diesel engines. Chiaramonti et al. (2007) investigated the use of pyrolysis oil gas turbine combustors, showing that the fuel needs to be preheated to reduce its viscosity, as well as filtered to reduce its ash and solid contents. In general, experience with bio-oil combustion in gas turbines is still fairly limited (refer also to Lupandin et al., 2005), and further research is required until its application on a commercial scale is achieved.

All pyrolysis systems produce some char as a by-product (Gaunt and Lehmann, 2008), which is often referred to as bio-char or sometimes as ‘agri-char’ when used as a soil amendment. Biochar is very stable compared with uncharred biomass (Baldock and Smernik, 2002) and has an inherent energy value that can be utilised to maximise the energy efficiency of the pyrolysis facility.

Various parameters determine the proportions of the three pyrolysis products (see above). Fixed carbon and the carbon content in the char are enhanced by increasing the temperature, and the latter, for instance, can constitute 80wt.% at 500°C and 92wt.% at 600°C, as shown in Table 17, below (Amutio et al., 2011). The relatively low ash content in lignocellulosic biomass is reflected in the low ash yields from bio-char (DeSisto et al., 2010; Kumar et al., 2010; Oasmaa et al., 2010; Venderbosch and Prins, 2010; and Cuña Suárez et al., 2010). The study by Amutio et al. (2011) also shows that temperature affects the calorific value of the initial biomass by 50% at 600°C. The heating values of the chars obtained at 500°C and 600°C are much higher (30.4 and 39.9MJ/kg respectively) than for other solid fuels such as soft coal (29MJ/kg) and lignite (20MJ/kg).

Biochar has been described as a possible means to improve soil fertility as well as other ecosystem services, and to sequester carbon to mitigate climate change (Laird, 2008; Lehmann et al., 2009; Lehmann et al., 2011). The observed effects on soil fertility have been explained mainly in terms of a pH increase in acid soils (Van Zwieten et al., 2010), or improved nutrient retention through cation adsorption (Liang et al., 2008). However, it has been established, both through field research (Lehmann et al., 2003a; Rondon et al., 2007) and observation of situations where historically bio-char has been applied to soil (Lehmann et al., 2003b), that applying biochar to soil enhances plant growth. When applied to soil, biochar improves the supply of nutrients to crops as well as the soil’s physical and biological properties (Glaser et al., 2002). This results in increased crop yields in low-input agriculture, and an increased crop yield per unit of fertiliser applied (fertiliser efficiency) in high-input agriculture, as well as in reductions in off-site effects such as run-off, erosion, and gaseous losses (Gaunt and Lehmann, 2008).

Table 17: Influence of pyrolysis temperature on bio-char properties

	400°C	450°C	500°C	600°C
Ultimate analysis				
C (wt.%)	73.3	75.2	82.7	89.4
H (wt.%)	3.7	3.6	2.9	1.4
N (wt.%)	0.2	0.1	0.1	0.1
O (wt.%)	20.6	18.7	11.4	5.7
Proximate analysis				
Volatile matter (wt.%)	37.6	33.3	23.5	14.1
Fixed carbon (wt.%)	60.2	64.3	73.6	82.5
Ash (wt.%)	2.2	2.4	2.9	3.4
LHV (MJ/kg)	21.6	27.4	30.4	39.9
Surface characteristics				
BET surface (m^2/g)	1.9	2.2	16.2	73.2
Average pore diameter (Å)	472.1	443.5	389.2	64.6

Source: Amutio et al. (2011: 7)

Charcoal, also referred to as *black carbon* (BC), is hypothesised to have several positive impacts on soils (Glaser et al., 2002).

- Charcoal is an adsorbent, and when present in soils, it increases the soil's capacity to adsorb plant nutrients and agricultural chemicals, thereby reducing leaching of these chemicals to surface and ground water.
- Charcoal contains most of the plant nutrients that were removed when the biomass was harvested and has the capacity to slowly release these nutrients to growing plants.
- Charcoal is a relatively low-density material that helps to lower the bulk density of high-clay soils, increasing drainage, aeration, and root penetration, and it also increases the ability of sandy soils to retain water and nutrients.
- Charcoal is a liming agent that will help offset the acidifying effects of N fertilisers, thereby reducing the need for liming.

Some of the unintended consequences from applying biochar to soil are discussed by Kokaana et al. (2011), highlighting the physical and chemical characteristics of biochar, which can impact on the sorption, hence efficacy and biodegradation, of pesticides. As a consequence, weed control in biochar-amended soils may prove more difficult as pre-emergent herbicides may be less effective. Since biochars are often prepared from a variety of feedstocks (including waste materials), the potential introduction of contaminants needs to be considered before land application. Plant growth, as well as soil microbial and faunal communities may be affected particularly by metal contaminants. Furthermore, biochar may also influence a range of soil chemical properties, and rapid changes to nutrient availability, pH, and electrical conductivity need to be considered to avoid unintended consequences for productivity. However, most negative effects of biochar are due to the way in which biochar was manufactured and what feedstock was used for the production of biochar. Particularly when using lignocellulosic biomass from SRC plantations as a biochar feedstock, the level of toxic compounds are not considered a serious problem for applying biochar to soil.

The half-life of C in soil charcoal is in excess of 1000 years (Glaser et al., 2002). This means that charcoal applied to the soil will make a lasting contribution to soil quality, and the C in the charcoal will be removed from the atmosphere and sequestered in the soil for millennia (Laird, 2008).

Preliminary research by Rondon et al. (2005) suggests that nitrous oxide (N_2O) and methane (CH_4) emissions from the soil may be significantly reduced by applying biochar. It was found that CH_4 emissions were completely suppressed and N_2O emissions were reduced by 50% when biochar was applied to soil. Yanai et al. (2007) also found a suppression of N_2O when biochar was added to soil. The mechanisms by which N_2O and CH_4 emissions are reduced are not clear. However, the reduction in N_2O emissions observed by these authors is consistent with the more widespread observation that fertiliser is used more efficiently by crops in situations where biochar has been applied to the soil (Gaunt and Lehmann, 2008).

It should be stressed, however, that the effectiveness of using bio-char to mitigate climate change rests on its relative recalcitrance against microbial decay, and thus on its slower return of terrestrial organic C as carbon dioxide to the atmosphere (Lehmann, 2007). Both the composition of the decomposer community as well as the metabolic processes of a variety of soil organismal groups may be important in determining to what extent bio-char is stable in soils, as these have been established for wood decay (Fukami et al., 2010).

The majority of the C in the biochar is in a highly stable state and has a mean residence time of 1000 years or longer at a 10°C mean annual temperature (Roberts et al., 2010; Cheng et al., 2008; Lehmann et al., 2009) (refer also to Figure 21, below).

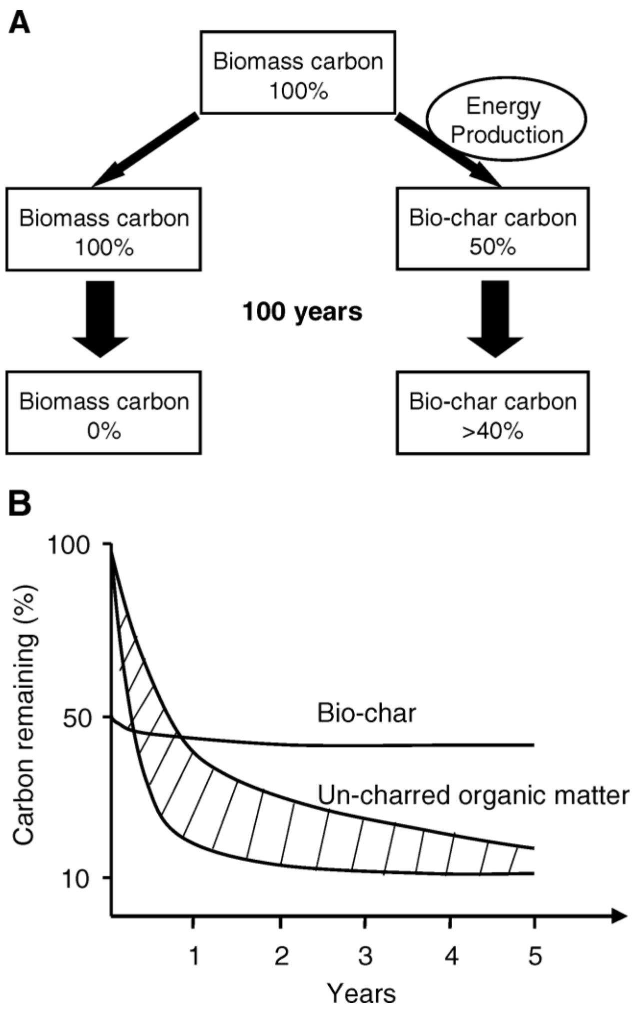

Figure 21: Schematic representation of biomass or bio-char remaining after charring and decomposition in soil

(A) C remaining from biomass decomposition after 100 years; C remaining after charring or pyrolysis. (B) range of biomass C remaining after decomposition of crop residues.

Source: Lehmann et al. (2006: 406)

4.3.2 Natural system boundaries: biological biomass production capacity

Biological biomass production is a central element of a bioenergy-related LCA, where all biological biomass production-related inputs and outputs are accounted for. The CO_2 uptake (and/or carbon uptake) of biomass via photosynthesis must be included. In most cases, a dynamic uptake model is not adequate or applicable in LCA studies; therefore, a simplified static approach to calculating the CO_2 uptake should be used (Jungmeier et al., 2003). The three main elements in biomass are carbon, oxygen and hydrogen, accounting for more than 96% of its composition, with the remainder being trace elements such as nitrogen, sulphur, or potassium.

Figure 22 gives a schematic representation the biological biomass production process via photosynthesis (PE International, 2011), illustrating that CO_2, radiation from the sun, and water are used to produce glucose, which is then converted in the metabolic cycle into lignin, cellulose and hemicellulose. Additionally, oxygen is generated; water is used as a reducing agent and is partially emitted; and the sun's radiation is converted into chemical energy.

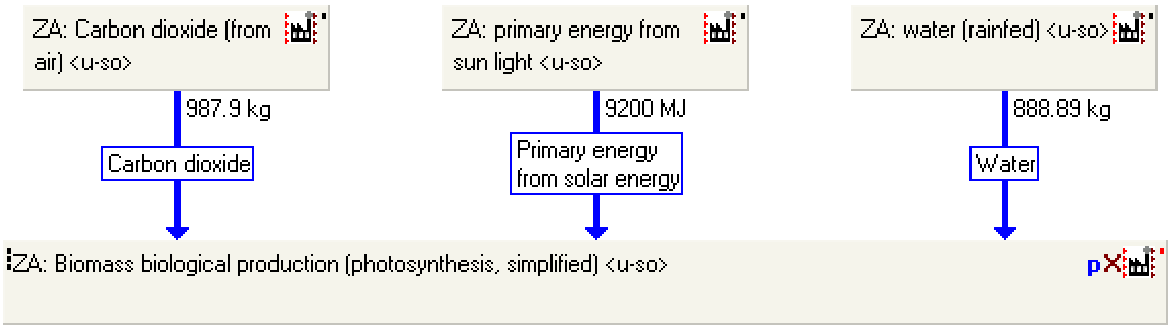

Figure 22: Biological biomass production via photosynthesis

Note:

For the production of one tonne of fresh biomass, 80wt.% MC, dry basis

Quantification of the amount of sequestered and stored CO_2 is based on the method proposed by Zimmer and Wegener (1996), who used a modified photosynthesis equation (Rödl, 2008). The general photosynthesis equation (refer to Equation 8, below) describes the structure of a hexose with a carbon content of 40%. In order to accommodate the difference in mass ratio, Zimmer and Wegener (1996) developed a molecule which is shown in equation (refer to Equation 9, below). Based on this equation, the inputs required to produce one tonne of lignocellulosic biomass can be calculated (refer to Equation 10, below) assuming that the energy required is equal to the energy contained in the biomass, i.e. 9.2MJ/kg (80% moisture content). However, it should be noted that this represents a simplified approach, since it is unknown how much actual energy is required to generate one tonne of wood.

Equation 8: General photosynthesis equation

$$6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

Equation 9: Adapted photosynthesis equation

$$8.4\ CO_2 + 12\ H_2O \rightarrow C_{8.4}H_{12}O_{5.4} + 8.7\ O_2 + 6\ H_2O$$

Equation 10: Inputs and outputs for producing one tonne of lignocellulosic biomass

$$1\,637kg\ CO_2 + 864kg\ H_2O \rightarrow 1000kg\ wood + 1069kg\ O_2 + 632kg\ H_2O$$

Table 18: Silvicultural production and other indicators for selected BPAs

Biomass demand area (BPA)[a]		BPA I	BPA II	BPA III	BPA IV
Demand point		Paarl	Worcester	Ashton	Rural Cederberge
Relatively Homogeneous Farming Area Group[a]		1-2	3-4	5-6	7-8
Potential tree species[b]		*Eucalyptus cladocalyx* (Sugar Gum)			*Acacia karoo* (Sweet Thorn)
Drought resistance[b]		High			High
Frost resistance[b]		Medium			Medium
Ease of cultivation[b]		Easy			-
Invasiveness[b]		Medium			None
Adaptability to site conditions[b]		High			High
Rotation length (years)		5	7	10	15
No. of rotations (coppices)		4 (3)	4 (3)	4 (3)	4 (3)
Stems per hectare (sph)		2000	2200	1800	1250
Usual height attained (m)		15	15	15	6
DBH attained (cm)[c]		10-14	10-14	10-14	10-14
MAI[d], whole tree (stems only)[e], t/ha/a	0% MC	15.0 (10.5)	10.0 (7.0)	5.0 (3.5)	2.8 (1.9)
	20% MC	18.0 (12.6)	12.0 (8.4)	6.0 (4.2)	3.3 (2.4)
	40% MC	21.0 (14.7)	14.0 (9.8)	7.0 (4.9)	3.9 (2.7)
	80% MC	27.0 (18.9)	18.0 (12.6)	9.0 (6.3)	5.0 (3.5)
Potential yield per rotation (stems only)[e], (t/ha)	0% MC	75 (53)	70 (49)	50 (35)	42 (29)
	20% MC	90 (63)	84 (59)	60 (42)	50 (35)
	40% MC	105 (74)	98 (69)	70 (49)	59 (41)
	80% MC	135 (95)	126 (88)	90 (63)	75 (53)

Notes:

[a] Four biomass procurement areas (BPAs) were selected based on their respective biomass productivity rates, which were estimated by an expert group (Theron et al., 2008) applying climate data for the so-called Relatively Homogeneous Farming Areas (RHFAs) (Von Doderer, 2009).

[b] Suitable tree species were identified (Theron et al., 2008) based on their expected productivity, drought and frost resistance, ease of cultivation, invasiveness, and adaptability to site conditions (Poynton, 1984).

[c] Diameter at Breast Height (DBH).

[d] Mean Annual Increment (MAI).

[e] The values in brackets indicate the biomass available when leaving branches, tops, etc. behind and only using the stemwood as bioenergy feedstock – see also Dovey (2009) and Kumar et al. (2011).

In this study, natural system boundaries refer, *inter alia*, to the biological biomass production capacity. The biological biomass production capacity is a function of a variety of variables such as the soil, ground and climate conditions of the location of the SRC plantations. As mentioned in section 2.3, 14 potential bioenergy conversion sites (demand points) were identified in the CWDM. Four demand points/biomass procurement areas (BPAs) were selected (namely, Paarl, Worcester, Ashton and Rural Cederberge), based on their different site conditions, with estimated productivity rates for woody biomass grown in an SRC system (relatively high, medium, low, very low). The productivity rates for each of the sites were estimated by an expert group (Theron et al., 2008) based on the climate data for each of the so-called Relatively Homogeneous Farming Areas (RHFAs), spatial units with relative homogeneity in terms of climate, terrain, soils, and resulting farming pattern (Elsenburg Landbou-Ontwikkelingsinstituut, 1990a, 1990b, 1991), which were grouped according to their respective climate data and proximity (Von Doderer, 2009). Table 18, below, shows the biomass productivity and other relevant silvicultural data for the biomass procurement areas (BPA) of the four selected demand points.

As is also mentioned in section 2.3, although actual drought and frost resistant species such as *E. cladocalyx* and *A. karoo* were identified for producing woody biomass in the CWDM, in order to keep the number of variables for the bioenergy feedstock to a minimum, but somewhat representative sample, a hypothetical 'bioenergy tree' with average values for its chemical composition (refer to Table 5) was used in the LCA model.

4.3.3 Natural system boundaries: land-use change and ecosystem carbon storage

Land use and management influence a variety of ecosystemic processes that affect greenhouse gas fluxes (see Figure 23, below), such as photosynthesis, respiration, decomposition, nitrification/denitrification, enteric fermentation, and combustion. These processes involve transformations of carbon and nitrogen that are driven by biological (activity of microorganisms, plants, and animals) and physical processes (combustion, leaching, and run-off) (Paustian et al., 2006).

Land use is recognised as the main driver of soil degradation, although impacts on soil quality can also be beneficial, depending on land management practices. In fact, in contrast to annual crops, perennial cropping systems, such as SRC willow systems, tend to accumulate soil organic carbon (SOC) and can serve to remediate contaminated soil (Brandão et al., 2010).

Land-use change due to bioenergy production can occur in two ways: (i) directly, when uncultivated land, pasture, etc. is converted to produce energy crops (e.g. grassland is used to cultivate cereals for bioethanol), or (ii) indirectly, through displacing food and feed crop production to new land areas previously not used for cultivation. From an LCA perspective, direct land-use change is often straightforward and easy to include in the assessment – see, e.g. Reijnders and Huijbregts (2008) – although there are often uncertainties in the levels of carbon stock changes due to variations in local conditions and a lack of reliable field trial data.

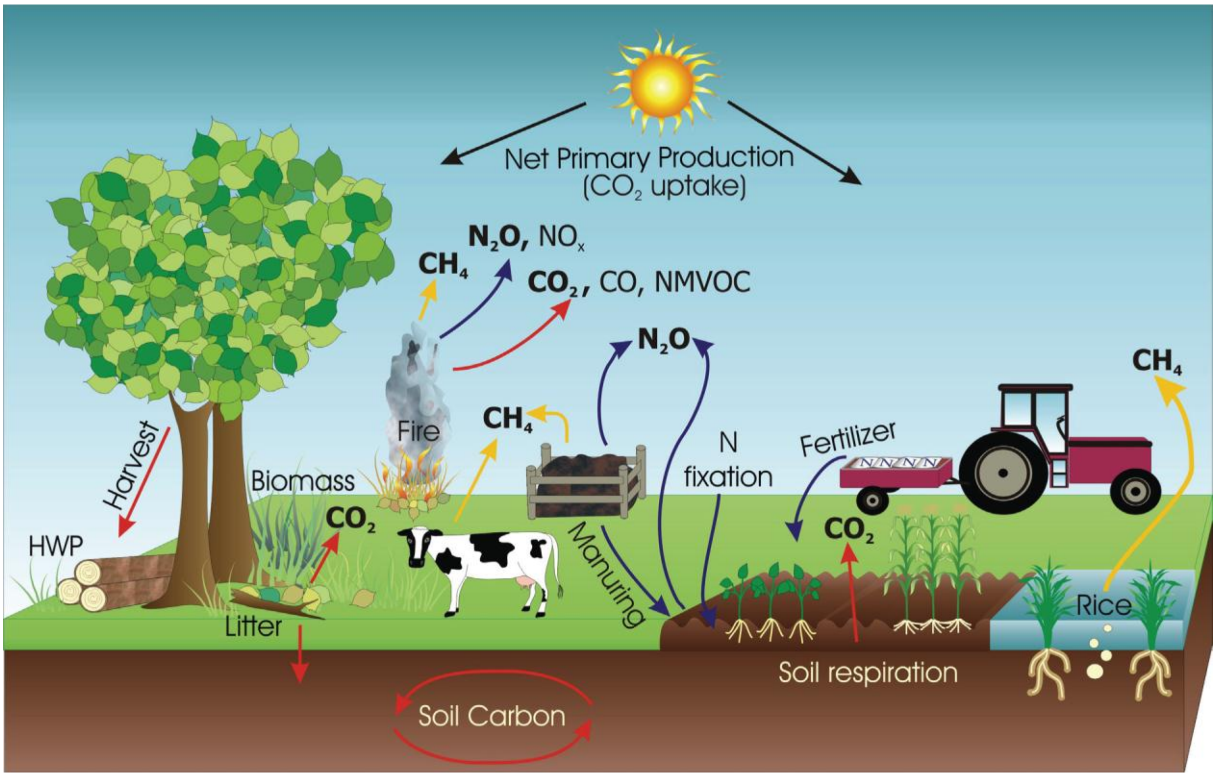

Figure 23: The main greenhouse gas emission sources/removals and processes in managed ecosystems

Source: Paustian et al. (2006: 1.6)

4.3.3.1 Direct land-use change

Direct land-use change (dLUC) occurs when new agricultural land is taken into production for feedstock for biofuel purposes, displacing a prior land use (e.g. conversion of forest land to sugarcane plantations), thereby generating possible changes to the carbon stock of that land. Depending on the previous use of the land and the crop to be established, there could be a benefit or a disadvantage: when a forest is converted to agricultural land for biofuel production, there will be a loss of carbon stocks; on the other hand, when set-aside land is taken into production, the carbon stock may increase (Cherubini et al., 2009: 437).

4.3.3.2 Indirect land-use change

Indirect land-use change (iLUC) (or leakage) occurs when land currently used for feed or food crops is switched to bioenergy feedstock production, and the demand for the previous land use (i.e. feed, food) remains, because the displaced agricultural production will move to other land where unfavourable land-use change could occur. GHG emissions from indirect land-use change are claimed to be even more important than emissions from direct land-use change (Cherubini et al., 2009: 438).

Indirect land-use change occurs outside the system boundary because of the displacement of services (usually food production) that were previously provided by the land now used for bioenergy. Emissions from iLUC are not as easy to calculate as dLUC because there are many drivers of land-use change. Therefore, it is difficult to ascertain precisely which land-use change is a result of the bioenergy system (Bird et al., 2010). Hence, indirect land-use change is not included in this study.

4.3.3.3 Carbon stock change

Changes in land use can potentially alter carbon stocks by releasing or sequestering soil and vegetation carbon (Mills et al., 2011, in preparation). Carbon is stored within the woody biomass of vegetation, the root biomass, the soil surface biomass, and in soil organic matter (microbial biomass) to varying degrees. Similarly, carbon stocks between areas may differ and change spatially and temporally as a result of natural variations in temperature and rainfall, successional dynamics, and disturbances (such as fire, diseases and pests).

Six factors affecting the accumulation of C within an ecosystem are identified by Mills et al. (2005: 183):

- C storage is a function of mean annual precipitation (MAP) and temperature. Soil C tends to increase with an increase in mean annual precipitation (Dalal and Mayer, 1987; Hontoria et al., 1999), probably because primary productivity tends to be a function of rainfall (Knapp and Smith, 2001), and organic matter inputs into the soil tend to be greater in mesic than in arid regions.
- C storage will increase with an increase in woody biomass.
- Frequent fires will lead to a decrease in C storage in both biomass (Tilman et al., 2000) and soils (Bird et al., 2000).
- Tillage will reduce C storage in biomass and soils (Tiessen et al., 1992; Gregorich et al., 1994; Aslam et al., 2000; Francis et al., 2001).
- The establishment or maintenance of a permanent cover of vegetation (e.g. pasture, thicket) will maintain or increase soil C (Dalal and Chan, 2001; Dominy and Haynes, 2002). The effect of pasture establishment on biomass C depends on the structure of the natural

vegetation. Pastures may accumulate more biomass C than natural grassland if a dense grass sward is established, but will have less biomass C than woody systems.

- Any of the above effects will be dependent on changes to, and the inherent chemical and physical properties of the soil (Oades, 1993; Zech et al., 1997; Percifal et al., 2000). The establishment of plantations on former grassland, for example, may be expected to reduce soil water content, improve soil aeration, and therefore reduce soil C storage (Birch, 1958).

The possible change of carbon storage pools in the forest (i.e. trees, soil and litter) brought about by removing wood from forests should be considered, at least as a qualitative description (Schlamadinger et al., 1997). The most important carbon compartments in forest ecosystems are living vegetation (trees and ground vegetation), dead organic matter and the forest soil (Jungmeier et al., 2003).

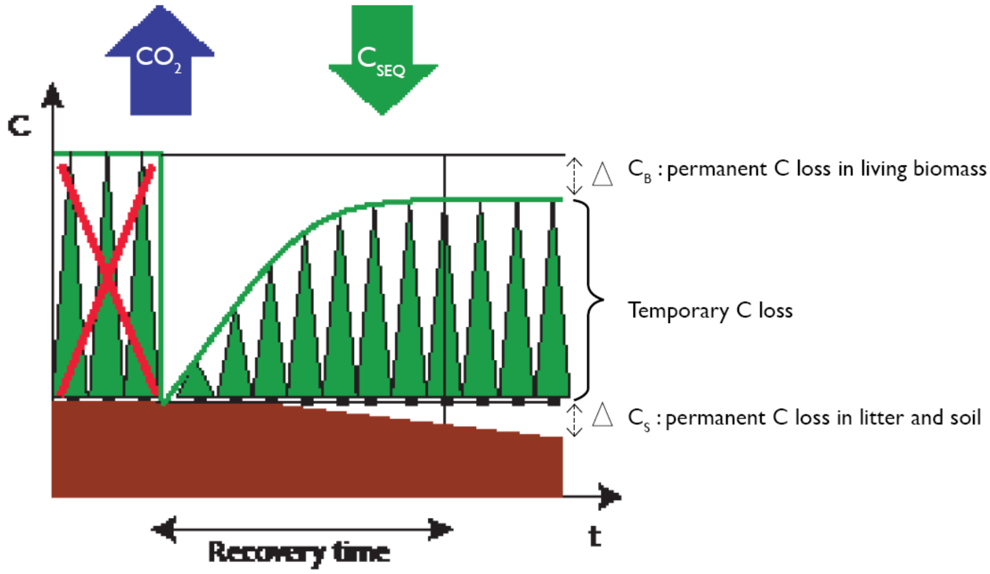

Figure 24: Temporary and permanent carbon stock losses produced by increased biomass use

Source: Bird et al. (2010: 62)

In interpreting the carbon cycle, it is important to consider the following aspects: assumed rotation period of the forest ecosystem, changes to carbon storage pools, landfill by wood-based waste, and recycling. Figure 24 illustrates the potential temporary and permanent losses of carbon over time due to land-use change or increased biomass use. Conversely, in some cases of land-use change, the carbon stock may increase; for instance, when changing from intensive agriculture to extensive forestry.

In order to account for the carbon stock change when introducing lignocellulosic biomass production in each of the biomass procurement areas, the current land-use types, their proportions and their respective carbon stocks had to be determined and compared with the expected carbon stocks of SRC plantations. The respective proportion for each land-use type that would be replaced by an SRC plantation for each biomass procurement area – presented in Table 19, below – has been derived from the data used in the land availability assessment (Von Doderer, 2009), which in turn is based on the original land cover categories developed by CSIR-ARC-Consortium (2000).

Table 19: Proportions of changed land use by introducing SRC plantations per BPA

No.	Identified land for biomass production[a]	Land cover[b]	Biomass procurement area			
			I	II	III	IV
1	Extensive dryland and improved grassland	CTCD[c]	-	60.6%	51.4%	44.9%
		IG[d]	-	0.4%	1.6%	0.1%
2	Fynbos, shrubland, and bushland	SLF[e]	50.0%	31.5%	33.2%	51.9%
		TBCF[f]	50.0%	7.5%	2.8%	3.1%
3	Intensive, permanent and temporary farmland	CPCI[g]	-	-	10.4%	-
		CTCI[h]	-	-	0.6%	-

Notes:
[a] Land cover categories as applied in Von Doderer (2009)
[b] Original land cover categories in CSIR-ARC-Consortium (2000)
[c] Cultivated, temporary, commercial dryland (CTCD)
[d] Improved grassland (IG)
[e] Shrubland and Low Fynbos (SLF)
[f] Thicket, Bushland, Bush Clumps, High Fynbos (TBCF)
[g] Cultivated, Permanent, Commercial, Irrigated (CPCI)
[h] Cultivated, Temporary, Commercial, Irrigated (CTCI)

Based on the land availability assessment, six of the land cover types present in the CWDM would be affected if SRC plantations were introduced. Each of the BPAs has an unique distribution of land cover types affected. However, due to the large extent of the area and the heterogeneity thereof, assessing the soil and production types of each potential site would go beyond the scope of this study. Thus, some generalisations were necessary. Only organic carbon (i.e. above- and below-ground carbon) is taken into consideration, since some factors contributing to the total carbon stock – such as the inherent chemical and physical properties of the soil – are unknown. Furthermore, each of the land cover types themselves already represent a variety of production types, e.g. cultivated, permanent, commercial, irrigated, which include any type of intensive agricultural production where permanent irrigation systems are installed, such as vineyards, deciduous fruit orchards, etc. Hence, production systems had to be selected that were somewhat representative for each land-use category, in order to give some carbon stock change estimates (see Table 20, below).

Table 20: Above- and below-ground biomass and its related carbon stock at equilibrium per land-use type and BPA

Land-use type:	**Fynbos, Shrubs[a]**				**Extensive (dryland) farming[b]**				**Intensive farming[c]**	**Biomass production[d]**			
Production system:	**-**				**Wheat**				**Lemon orchard**	**SRC plantation**			
Biomass procurement area:	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**	**I-IV**	**I**	**II**	**III**	**IV**
Biomass													
Above-ground biomass (kg/ha)	11351	10568	7492	6187	8571	2857	1429	2571	23 755	37500	35000	25000	20 830
Below-ground biomass (kg/ha)	13258	12343	8750	7226	4615	1538	769	1385	10 933	31 500	29 400	21 000	17 500
Average above- and below-ground biomass (kg/ha)	24609	22911	16242	13412	13187	4396	2198	3956	34 688	69 000	64 400	46 000	38 330
Carbon													
Above-ground organic carbon (kg/ha)	5 676	5 284	3 746	3 093	3 429	1 143	571	1 029	19 954	18 000	16 800	12 000	10 000
Below-ground organic carbon (kg/ha)	6 629	6 172	4 375	3 613	1 846	615	308	554	9 183	15 120	14 110	10 080	8 400
Average below- and above-ground carbon (kg/ha)	**12 305**	**11 456**	**8 121**	**6 706**	**5 275**	**1 758**	**879**	**1 582**	**29 138**	**33 120**	**30 910**	**22 080**	**18 400**
Carbon content in biomass (wt%)	50				40				50	48			
Root-shoot ratio (%)	117				54				46	48			
Ecosystem lifespan (a)	10				1				25	20	28	40	60

Notes:

[a] *Source: Cockx (2002)* Fynbos biomass quantity and carbon content depend on age of Fynbos vegetation; assuming an age of 10 years, values are derived from above-ground formula ($Biomass_{above-ground} = -0.2428 * age^3 + 7.1018 * age^2 + 131.73 * age + 8 * 10^{-8}$) and below-ground formula ($Biomass_{below-ground} = -0.2835 * age^3 + 8.2949 * age^2 + 153.86 * age + 9 * 10^{-10}$).

[b] *Source: Agenbag (2011)* The expected grain yields are 3000, 1000, 500 and 900kg/ha for BPAs 1-4 respectively, assuming a yield-biomass ratio of 0.35, a root-shoot ratio of 0.65, and a carbon content of 40%.

[c] Assuming a lemon orchid as a reference land-use type for intensive farming – all irrigated, average spacing 500 trees/ha, reaching full production after 8 years, with a plantation life span of 25 years, dry mass 144kg/tree (Goldschmidt and Golomb, 1982: 207), leaves renewed every two years, average carbon content assumed, 50%.

[d] Dry matter, based on productivity rates provided in Table 5, above, assuming a root-shoot ratio of 0.48 and a carbon content of 48%.

To determine an average organic carbon stock for intensive farming activities, the perennial production of lemons under irrigation was assumed. As mentioned above, C storage is a function of MAP and temperature. Since the lemon orchards are assumed to be irrigated, no distinctions are made for the different BPAs in producing biomass, neglecting the possible impact of temperature. Each 'off-tree' has a dry mass of 144kg with a carbon content of 50% and reaches full production after eight years. Assuming a spacing of 500 trees per hectare and a plantation lifespan of 25 years, as well as leaf renewal every two years, an average above- and below-ground carbon stock of around 29 tonnes per hectare was assumed.

Considerably less organic carbon is expected for annual farming activities, such as wheat production in a rain-fed dryland farming scenario. Average grain yields of 3, 1, 0.5 and 0.9t/ha (dry basis) are expected for BPAs I-IV respectively (Agenbag, 2011), and combined with a yield-aboveground biomass ratio of 0.35, a shoot-root-ratio of 0.65, as well as a carbon content of 40%, average above- and below-ground carbon contents of 5.2, 1.7, 0.8 and 1.6 t/ha for BPAs I-IV respectively have been taken into account.

For areas that are not actively used commercially, such as Fynbos areas, shrubland, and bushland, a Fynbos ecosystem was assumed. Based on the above- and below-ground biomass equations in Cockx (2002), an average age of ten years until fires destroy current vegetation – allowing the Fynbos vegetation to reproduce – and a carbon content of 50%, Fynbos average above- and below-ground carbon stocks of 12.3, 11.5, 8.1 and 6.7 t/ha for BPAs I-IV respectively have been assumed.

These values for the different land-use ecosystems assume an average biomass/carbon stock, incorporating initial growth, consumption, and decomposition processes. In SRC plantations, both above- and below-ground biomass is developed during the first rotation. Following the planting of the trees, the above-ground biomass is removed after each rotation (harvesting). Once the below-ground biomass is fully established during the first cycle, the biomass/carbon level is not expected to change until the stumps have been exterminated with spray, resulting in decomposition of the below-ground biomass, followed by re-establishment with improved genetic material. With 48% carbon content in the biomass (refer to section 2.4.2), BCA 1 accumulates an above- and below-ground living organic content of 33 tonnes per hectare, with organic content levels of 30.9, 22.1, and 18.4 for the remaining BPAs respectively.

Thus, when substituting current land-use types with a biomass SRC production system, the carbon stock will in most cases increase to varying degrees, except when substituting intensive farming production (i.e. lemon orchards) in BPAs III and IV (see Table 20, above).

4.3.4 Time boundaries

Since this study is aimed at comparing bioenergy systems and identifying the most sustainable one, this LCA can be defined as change-oriented and thus prospective. The functional unit, the annual production of electricity, also specifies the time boundary for the LCA, i.e. one year.

However, for the financial assessment, a longer time boundary is required in order to determine the profitability of the different bioenergy alternatives in terms of net present value (NPV), and internal rate of return (IRR). As is commonly accepted for the financial-economic analysis, an economic business cycle of 20 years for the conversion plant has been assumed. Depending on the BPA/demand point, this time boundary has been extended by the respective rotation lengths for the SRC plantations, since a sustainable supply of biomass needs to be ensured. Hence, the time boundary is 25 years for BPA I, 27 for BPA II, 30 for BPA III and 35 for BPA IV.

4.4 Conclusions

Chapter four encompasses the goal and scope definitions, the first phase of the life-cycle assessment of lignocellulosic-biomass bioenergy systems in the Cape Winelands District Municipality. To provide a reference, the functional unit was defined, for which the input and output process data of the following chapter are normalised, providing the basis on which the final results are presented. Furthermore, the system boundaries were discussed, which were specified in terms of several dimensions, such as boundaries in relation to the natural system (i.e. biological biomass production capacity and land-use change-related carbon stock changes); time boundaries, which are strongly linked to the functional unit; as well as the technical system boundaries. At the beginning of section 4.3.1, schematic illustrations (Figure 9 and Figure 10) show the various bioenergy system production phases or pathways leading to a set of 37 bioenergy system alternatives (refer to Figure 11). Each production phase, subdivided into primary biomass production; harvesting and primary transport; biomass pretreatment, including comminution, drying and mobile fast pyrolysis; as well as secondary transport; biomass upgrading and final conversion into electricity were also discussed. This gives some general background information on available technologies and applications.

The second phase of a life-cycle assessment (LCA), the life-cycle inventory (LCI), is presented in the following chapter. Information is gathered about the inputs and outputs for all processes and activities of the 37 lignocellulosic bioenergy systems (LBSs), which not only includes the specification of each unit process on productivity and environmentally relevant flow data, which is commonly required for an LCI, but also financial-economic data, in terms of costs, as well as socio-economic data, in terms of direct employment creation potential.

5 CHAPTER: LIFE-CYCLE INVENTORY

5.1 Introduction

The previous chapter describes the first phase of a life-cycle assessment, defining the goal and scope for assessing a set of 37 alternative lignocellulosic bioenergy systems (LBSs). The functional unit is set as $39.6GWh_{el}$, the annual output of electrical energy of a 5-megawatt conversion system on 330 days per year. The geographical boundaries for the LCA are set by the extent of the Cape Winelands District Municipality, describing also the natural system boundaries in terms of biomass productivity and land use, and related carbon stock changes for four so-called biomass procurement areas (Paarl, Worcester, Ashton and the Rural Cederberge). Furthermore, the technical system boundaries are defined, subdivided into various production phases such as primary biomass production, harvesting and primary transport; biomass pretreatment, including comminution, drying and fast-pyrolysis; as well as secondary transport, biomass upgrading and final conversion into electricity. Each production phase is discussed and general background information on available technologies and applications is given.

The life-cycle inventory (LCI) for each of the 37 lignocellulosic bioenergy systems is discussed in Chapter 5, representing the second phase of an LCA. In the life-cycle inventory analysis, information is gathered about all process-related inputs and outputs in the studied system. For each process, qualitative and quantitative data, i.e. relating to machinery and equipment, are assumed, and related productivity is specified, not only in terms of environmental input and output flows, which are typical for an LCI, but also by considering related financial-economic (capital and operational expenditures, income from selling electricity and related by-products such as thermal energy or bio-char), as well as socio-economic (direct employment creation potential) data.

5.2 Primary production of biomass

This represents the initial phase in the life cycle, which is the same for all 37 lignocellulosic bioenergy systems. Besides taking all the activities and processes in the establishment and maintenance of the SRC plantation into account, this phase also includes the carbon stock change per hectare and the land-use type of the respective biomass procurement areas (BPAs). Figure 25**,** below, shows the GaBi 4.4 LCA software interface for the primary production of biomass (PE International, 2011).

The establishment of an SRC plantation requires sufficient site preparation. Site preparation entails the clearing and cultivation of plantation areas. The clearing can be divided into two steps, mechanical and chemical land preparation. Mechanical land preparation consists of the removal of shrubs and trees in order to improve access for establishment operations, to allow effective cultivation, and to remove cover to deter browsing animals. Chemical land preparation is aimed at removing the remaining competing vegetation.

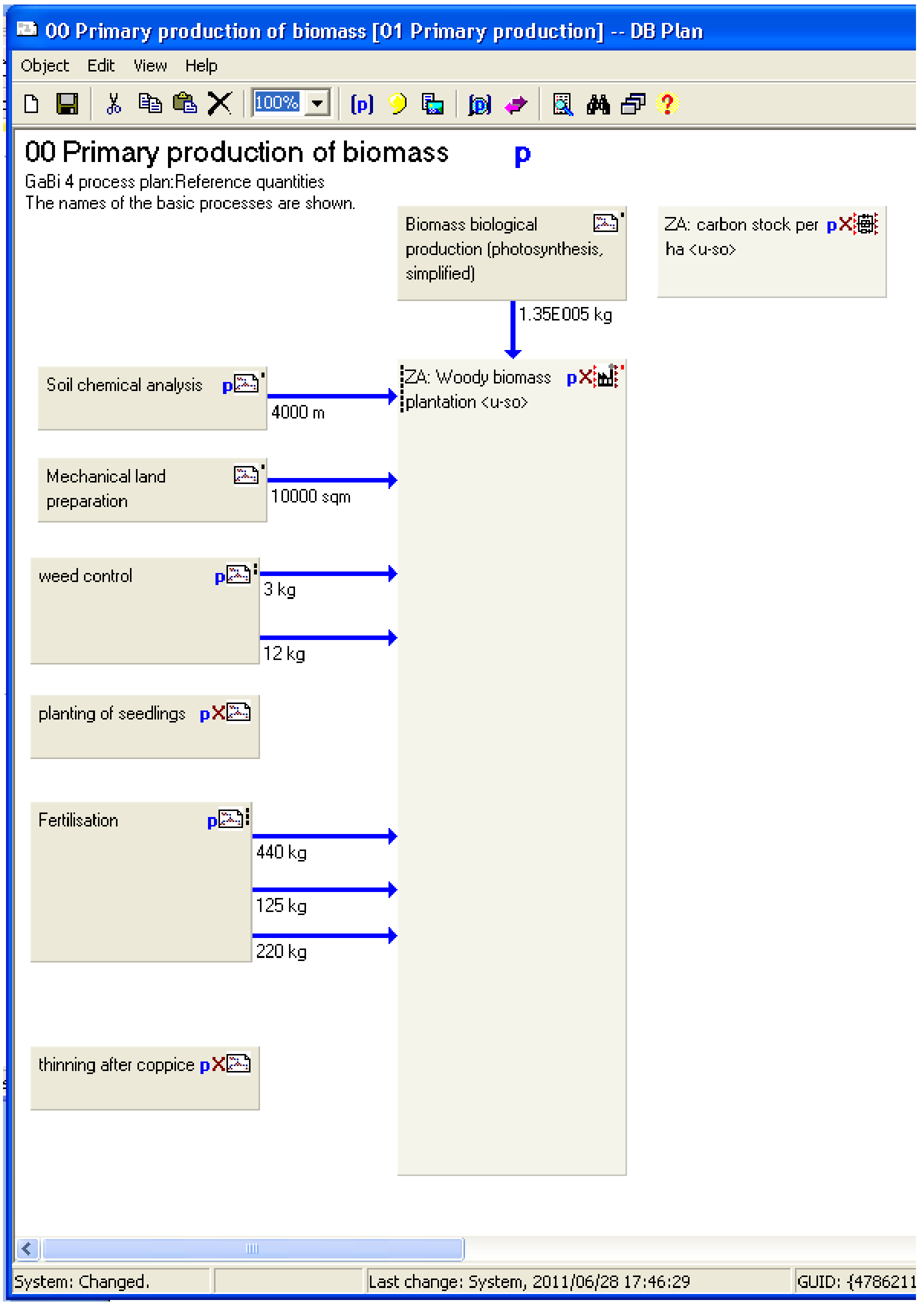

Figure 25: GaBi 4.4's LCA software interface illustrating the primary biomass production phase

Source: PE International (2011)

5.2.1 Mechanical land preparation

In the case of a heavy infestation of shrubs and trees, as well as when dealing with poor site conditions (i.e. instability), very rough ground conditions and steep slopes, ripping should be undertaken with heavy machinery such as bulldozers. However, since more than 80% of the identified SRC's biomass production areas are less steep than 20% (see Table 2) and sandy soils in the CWDM are predominant, it was assumed for all alternatives that a medium to light infestation of competing vegetation was a given, and that, therefore, using agricultural equipment (e.g. a tractor-plough combination) would be sufficient. Research on commercial timber and pulp wood production in South Africa shows that complete strip ploughing is the best method for establishing eucalypts (Viero, 2004).

Based on data from the *Guide to Machinery Costs* (Lubbe et al., 2011), it takes about 2.47h/ha for mechanical land preparation using a four-wheel-drive, high-power-demand tractor (67kW) combined with a five-shank, spring-tine chisel plough. The fuel consumption was assumed to be 12.06 litres per hour, resulting in fuel costs of R297.88 per hectare (ha) (a conservative fuel price for both diesel and unleaded petrol of R10/l was used throughout the multi-period budgeting models). The costs for the tractor operator were assumed to be R26.45/h (R65.33/ha). The capital investment costs for the tractor and for the plough were estimated at R435 to R450 and R32 to R100 respectively. Taking depreciation; licencing and insurance; repairs and maintenance costs, etc. into account, but excluding interest, the hourly cost for the tractor amounted to R201.59 and R15.41 for the plough. A figure for interest per annum of 10% for the machinery was included, and thus the total costs for mechanical land preparation were assumed to be R677.92/ha.

Resource consumption and emissions for the mechanical land preparation are captured in the LCA using the LCI process for soil cultivation (heavy ploughing), as provided in the software database (PE International, 2006).

5.2.2 Chemical land preparation and maintenance

Chemical land preparation and maintenance are required not only to remove the remaining competing vegetation, but also to allow purposeful and effective fertilisation, i.e. for their secondary effects, and therefore to enhance the growth rate of the trees, particularly during the first years after planting, until canopy closure is reached.

Table 21**,** below, indicates the assumed time of herbicide applications, the number of applications and the amount of herbicide per hectare applied throughout the lifetime of the SRC plantation. It must be noted that weed control operations might differ, depending on factors such as site conditions, the magnitude of infestation of competing vegetation and the growth rate/competitiveness of the grown crop. Additional information on weed control in plantation forests/woodlots can be found in Little et al. (1997). For both weed control prior to and post harvesting, the same herbicide can be applied, but at different levels of concentration Du Toit (2009).

Two to three harvests after coppicing can be done following the first harvest after the planting of the trees. If the SRC plantation is to be continued after 3-4 rotations, it might be beneficial to plant improved genetic material. To do this the existing stumps must be killed, and the new trees must be planted between the original lines, allowing the old stumps to decompose.

Table 21: Weed control operations

Rotation	Year	Broadcast spray l/ha	Cone spray l/ha	Total (l/ha)	Comment
1	0	6	4	10	One broadcast spray prior to planting; one cone spray operation post planting
	1		8	8	Two (cone spray) weed control operations per year at 4l/application
	2		8	8	
	...		4	4	To be continued until canopy closure is reached
2	0		8	8	Two (cone spray) weed control operations per year at 4l/application to support coppice shoots
3	0		8	8	
4	0		8	8	
X	X	6		6	Elimination of competing vegetation and killing of old stumps as preparation for new crop
	Total:	12	48	60	

Source: Du Toit (2009)

In order to account for the impact of weed control in the LCA, an average amount of herbicides per hectare was allocated per rotation over the lifetime of the SRC plantation. In total, 60 litres of herbicide are applied per hectare over the lifetime of the plantation, i.e. 15l/ha are sprayed per rotation. The cost for herbicides per hectare and rotation were estimated at R421. Additional material costs of R73/ha/rotation were added for the pressure sprayers for the manual operation (the purchase price is R389 per unit).

Weed control operations post planting are more time-consuming, so only a manual cone spray operation is done to avoid damage to the crop. Following the silvicultural guidelines of best operating practices (BOP) (Forestry Solutions, 2007j), the total treatment of an area prior to planting takes about 1.4 to 1.6 workdays per hectare (assuming a vegetation ground cover of 40-59% and a slope of up to 25%), whereas the coneing of the same area, i.e. weed control post planting, will require 3.1 to 3.3 workdays. Over the lifetime of the plantation, a total of 41.4 workdays are required, assuming an average value of 1.5 and 3.2 workdays respectively. Based on 9 hours per workday, farm workers will spend a total of 373 hours per hectare for weed controlling operations over the lifetime of an SRC plantation. With an agricultural minimum wage (AMW) of R6.74 per hour (RSA, 2011), the labour costs amount to R628.50 per hectare and rotation. Furthermore, additional costs of R189 were allocated per hectare and rotation for transportation, i.e. the supply of the chemicals to the farm, as well for as the transportation of farm workers, chemicals and other materials to and from the SRC plantation were specified as R2.82 per kilometre using a light duty vehicle (LDV) (two-wheel drive, diesel), commonly used on South African farms (Lubbe et al., 2011). In total, the cost for weed control amount to R1 312/ha/rotation.

5.2.3 Planting of seedlings

A central operation for the establishment of an SRC plantation is the unit process ‘planting of seedlings’, which includes preparation of planting pits at the required spacing (depending on the recommended stems per hectare, planting of the seedlings, and blanking). The term *blanking* refers to the replacement of dead seedlings shortly after planting; *replanting* describes, in forestry terms, the total replanting after clear-felling. The production costs of seedlings in nurseries, as well as the transport costs from the nurseries to the biomass production sites were not included.

Table 22: Planting and blanking productivity and costs (2011)

Planting	**Unit**	**Biomass procurement area (BPA)**			
		I	**II**	**III**	**IV**
No. of trees/ha	sph	2 000	2 200	1 800	1 250
Work hours per ha [a]	h/ha	45	49.5	40.5	28
Labour costs per ha [b]	R/ha	303	334	273	190
Planting material [c]	R/ha	2 000	2 200	1 800	1 250
Total planting costs	R/ha	2 303	2 534	2 073	1 440
Blanking	**Unit**	**I**	**II**	**III**	**IV**
Mortality rate	%	5	5	5	5
Trees to be replaced	No. of trees/ha	100	110	90	63
Work hours per ha[d]	h/ha	0.43	0.47	0.39	0.33
Labour costs per ha [b]	R/ha	2.90	3.17	2.63	2.22
Planting material [c]	R/ha	100	110	90	63
Total blanking costs	R/ha	103	113	93	65

Notes:

[a] *Source: Forestry Solutions (2007i).*

[b] Based on an agricultural minimum wage of R6.74 per hour.

[c] Assuming a seedling costs of R1.00/plant for *Eucalyptus spp.* and *Acacia karoo*.

[d] *Source: Forestry Solutions (2007g).*

Based on best operating practices, a worker is assumed to plant around 44 trees per hour, which includes both preparing the planting pits and planting the seedlings (Forestry Solutions, 2007i). Furthermore, a seedling mortality of 5% was assumed, resulting in a blanking productivity of 0.43, 0.47, 0.39 and 0.33 for biomass procurement areas I-IV respectively. Costs for labour of R6.74 per hour (RSA, 2011) and for seedlings of R1.00 per plant (Du Toit, 2009) were assumed.

5.2.4 Fertilisation

An important variable in LCA studies is the contribution to net greenhouse gases (GHG) emissions of N_2O, which results from the application of nitrogen fertiliser and the decomposition of organic matter in the soil (Stehfest and Bouwman, 2006). Applying fertiliser to agricultural land has an effect on the nutrient balance of the soil. Emissions from fields vary, depending on soil type, climate, crop, tillage method, and fertiliser and manure levels (Larson, 2005). The uncertainties concerning actual emissions are magnified by the high global warming potential of N_2O, which is 298 times greater than that of CO_2 (Forster et al., 2007). The impacts of N_2O emissions are especially significant for annual biofuel crops, since fertilisation levels are greater for these than for perennial crops. Crops grown in high rainfall environments or under flood irrigation have the highest N_2O emissions, as denitrification, the major process leading to the production of N_2O, is favoured under moist soil conditions where oxygen availability is low (Wrage et al., 2005).

Nitrogen fertilisers contribute to the environmental impact of bioenergy systems because (i) their production is energy intensive, (ii) their production releases significant quantities of nitrous oxide, and (iii) a proportion of the nitrogen added to agricultural soils, in the form of fertiliser, is converted to N_2O, a potent greenhouse gas, and released to the atmosphere.

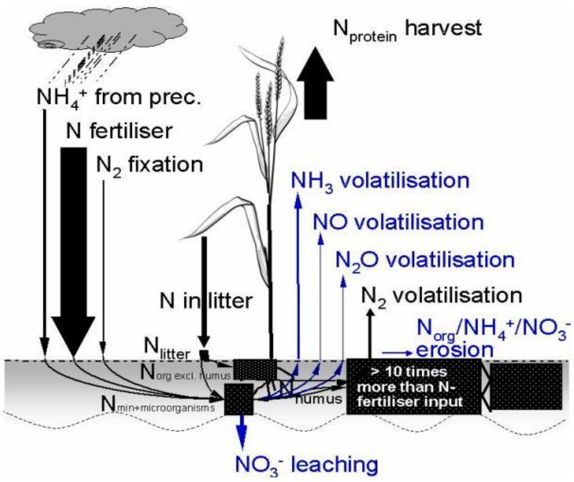

Figure 26: Proliferation pathways of nitrogen for agricultural land

Source: PE International (2007)

Many LCA studies neglect N_2O emissions; those that include N_2O often utilise default emission factors published by the Intergovernmental Panel on Climate Change (IPCC), which estimates emissions from several sources (IPCC, 2006) as follows (refer also to Figure 26, above):

- Volatilisation of N as NH_3 at a rate of 10% of total N in the case of synthetic N application, or 20% of total N in the case of manure application. Another study estimates these percentages to be much lower, around 2% (Van den Broek et al., 2000). One percent of the N in the NH_3 is then converted to N_2O.

- Direct soil emissions of N_2O at 1% in the case of synthetic N, and 2% in the case of manure (mean values). With respect to runoff and leaching to groundwater as nitrate (30% of total N applied), 0.75% thereof is converted to N_20.

The resulting effect is that 1.325% of synthetic N fertiliser is emitted as N in N_2O. However, for dry climates, as found in the CWDM, where leaching is unlikely to occur, the IPCC guidelines suggest a lower value of 1.1wt.% for the conversion factor of synthetic N inputs to N_2O. The nitrous oxide release (kg/ha/a) can therefore be calculated as outlined in Table 23, below:

Table 23: Emission factors from synthetic nitrogen inputs (%)

Emission factors [a]	**Source**	**Conversion factor [b] (C_F)**	**Formula**
N_2	Dämmgen (2006)	10.0	$N_2 = M_F C_F$
N_2O-N	IPPC (de Klein et al., 2006: 2492), Stephenson et al. (2010)	1.1	$N_2O = M_F C_F \frac{44}{28}$
NH_3-N	Doehler et al. (2002), Van den Broek et al. (2000)	2.0	$NH_3 = M_F C_F \frac{17}{14}$
NO	Dämmgen (2006)	0.7	$NO = M_F C_F$
NO_3^-	Stephenson et al. (2010)	0.0	$NO_3^- = M_F C_F$

Notes:
[a] from synthetic nitrogen inputs
[b] C_F, % from input

Similar for weed control, the assumed fertilising operations are based on general recommendations for sandy and clayey soils typically found in the CWDM (Du Toit, 2009). For individual sites, however, it is advisable to employ a soil chemist to undertake a soil chemical analysis in order to identify the appropriate fertiliser mix for the maximised growth of the SRC plantation. A Nitrogen

(N), Phosphate (P), and Potassium (K) mix for both a sandy as well as for a clayey soil type was recommended (see Table 24, below). For the LCA, in all primary production scenarios, a sandy soil type is assumed with a fertiliser mix (N-P-K) per tree of 30, 20 and 15 grams respectively.

Table 24: Recommended fertiliser mix per tree for different soil types

Active ingredient	**On sandy soils (g/tree)**	**On clayey soils (g/tree)**
Nitrogen (N)	30	15
Phosphate (P)	20	15
Potassium (K)	15	10

Source: Du Toit (2009)

In total, 12 fertiliser applications are recommended over the lifetime of the SRC plantation (see Table 25, below). Therefore, accounting for the impact of fertilisation in the LCA, an average of three fertiliser applications per rotation were assumed.

Table 25: Fertiliser application over lifetime of SRC plantations

Rotation	**Year**	**Number of applications**	**Comment**
1	0	3	One application at time of planting; two more applications during course of the first year
	1	3	Three applications each in year one, and two after planting to enhance growth rate/competitiveness of crop
	2	3	
	...	0	Fertilisation to be continued until canopy closure has been reached
2	0	1	To support above-ground biomass growth, one fertiliser application post harvesting
3	0	1	
4	0	1	
X	X	-	If SRC plantation is to be continued, it is recommended to plant new, improved genetic material; hence, fertilisation cycle starts anew.
Total		12	

Source: Du Toit (2009)

The costs of the respective fertilisers were obtained from Yara (2009) and are listed together with the required concentrations and amounts in Table 26, below. For sandy soils, the cost per application and tree are R0.92, and for clayey, soils R0.59 respectively. The cost per hectare depends on the amount of assumed stems per hectare (sph) – see Table 18, above.

Table 26: Fertiliser products, respective concentrations, and prices per ton (2011)

Active ingredient	Fertiliser Product	Concentration of active ingredient	Price/ ton (R/t)	Amount (g/tree) of fertiliser required	
				Sandy soils	Clayey soils
Nitrogen (N)	KAN28	28%	R3 350	107	54
Phosphate (P)	Maxifos 20P	20%	R3 780	100	75
Potassium (K)	KCL	50%	R5 980	30	20

Similar to the weed control operation, the manual labour costs are based on the agricultural minimum wage for 2010, i.e. R6.74 per hour, and – extrapolated from the best operating practices (BOP) – work efficiency for fertilising circles (fertiliser buried) of 0.93 minutes per tree (Forestry Solutions, 2007h). Additional costs were included for the transportation of fertilisers to the farm, and the transportation of farm workers, fertilisers and other material to the SRC plantation, as stated in Table 27, below. In total, the cost of fertilisation amounts to R2 654/ha/rotation for BPA I; and R2 919, R2 389, and R1 659 for BPAs II, III, and IV respectively.

Table 27: Average fertilising cost per ha and rotation on sandy soils in the CWDM (2011)

Cost item	BPA I	BPA II	BPA III	BPA IV
Fertiliser (R/ha)	R1 833	R2 016	R1 649	R1 145
Transport (R/ha)	R194	R214	R175	R121
Labour (R/ha)	R627	R690	R564	R392
Total (R/ha)	R2 654	R2 919	R2 389	R1 659

5.2.5 Thinning of coppice shoots

After clear-felling an SRC plantation, coppice shoots are allowed to resprout in order to regenerate the section. Once coppice shoots reach a height of between 1.5m and 2m, they should be reduced to between one or two shoots per stump (Little and Du Toit, 2003). The aim is to achieve the same tree density that was used in the first planting operation, relative to the stand target concerned. More than one shoot per stump can be left to make up for the mortality of neighbouring stumps.

As mentioned above, this procedure can be repeated at least two to three times after the initial planting. Thereafter, it is recommended that new, genetically improved tree material be planted between the original planting lines, after killing the original stumps with contact herbicides and allowing them to decompose (Du Toit, 2008).

Thinning, as the reduction of coppice shoots is also called, takes about 16 hours per hectare, resulting in manual labour costs of R108/ha, based on an AMW of R6.74 per hour. Furthermore, costs of R28/ha (R2.82/km for LDV, two-wheel drive, diesel) for transporting farm workers and materials to and from the site were also included. For the LCA, an average of 7.5km per rotation was assumed.

5.3 Harvesting and forwarding

As mentioned in section 4.3.1.2, five harvesting systems (HS) are modelled in this study, entailing three different harvesting technologies and three types of primary transportation (also referred to as forwarding or extraction). The harvesting technologies modelled are motor-manual machinery, mechanised forestry machinery, and modified agricultural machinery. A forwarder fitted with a crane; a tractor pole-trailer combination loaded and unloaded, either manually or with a three-wheeler loader; or a tractor-container trailer combination were assumed for primary transport.

5.3.1 Harvesting system I

In the case of harvesting system I (LBSs 1-8, see Figure 11), whole trees are felled using chain-saws, left in-field for several weeks for air-drying, and then transported to the roadside with a forwarder. The loading and unloading are executed by the forwarder operator, using a crane fitted to the forwarder.

As suggested by Schif (2010), the STIHL MS 361 chainsaw (3.4kW) is well suited to small-tree harvesting, consuming an assumed 1.7 litres (two-stroke blend) per productive machine hours (PMH) and 1kg/PMH of lubricants (e.g. chain oil). The fixed cost per PMH was assumed to be R9.52; the variable costs (e.g. repairs and maintenance, fuel and lubricants) amount to R29.72/PMH, resulting in total machinery costs of R39.24/PMH (R21.80/h). The chainsaw operator costs are R3 000/month (R16/h, R28.8/PMH), assuming a shift length (also referred to as a workday) of nine hours, of which five are counted as PMH, the remainder being allocated to non-productive work such as setting up, servicing and walking in the compartment. Hence, the total costs per PMH are R68.04 or R37.80/h.

A productivity rate of 54 trees per hour (felling only) was extrapolated from data provided by Forestry Solutions (2007a), based on industrial daily production targets which, *inter alia,* depend on variables such as tree species, tree height, tree branching, competing vegetation and ground conditions.

For the LCA, the Stihl MS 441 chainsaw process dataset provided in the GaBi database (PE International, 2006) was modified according to the above-stated input specifications and emission data provided by Schif (2010).

Table 28, below, sets out the productivity rates and costs for harvesting system one for each of the activities per biomass procurement area based on the corresponding number of trees per hectare (stems per hectare or sph) and the biomass yield per hectare and rotation.

Table 28: Harvesting system I – productivity rate and costs per hectare for each BPA (2011)

Biomass procurement area (BPA)		**BPA I**	**BPA II**	**BPA III**	**BPA IV**
Stems per hectare (sph)		2 000	2 200	1 800	1 250
Yield/rotation	t/ha (80% MC, whole tree)	135	126	90	75
	t/ha (40% MC, whole tree) [a]	105	98	70	59
Motor-manual harvesting	Productivity (trees/hour) [b]	54			
	Time (h/ha)	37	41	33	23
	Productivity (t/h)	3.65	3.09	2.70	3.24
	Cost (R/ha)	R2 520	R2 772	R2 268	R1 575
Extraction with forwarder [c]	Max. payload capacity	14t/load (22.40m^3/load)			
	Bulk density (logs)	0.375			
	Cycle length (min) [d]	42			
	Productivity (t/h)	12			
	Time (PMH/ha)	8.75	8.17	5.83	4.92
	Cost (R/ha)	R5 122	R4 781	R3 415	R2 878
Cost (R/t)	Harvesting	R19	R22	R25	R21
	Forwarding	R49	R49	R49	R49
	Total	R67	R71	R74	R70

Notes:

[a] Motor-manual harvesting entails felling only.
[b] Productivity for chainsaw application derived from industrial production standards (Forestry Solutions, 2007a).
[c] Forwarder John Deere/Timberjack 1410D.
[d] Forwarding productivity derived from industrial production standards (Forestry Solutions, 2007f).

Following the air-drying of the biomass to moisture content levels of around 40% (dry basis), the biomass is extracted with dedicated forestry machinery. For this study, the John Deere/Timberjack 1410D (129kW) with a payload capacity of 14t/load (22.40m^3/load) and a fuel consumption of 10.28l/PMH was assumed. As practical experience indicates that the volumetric capacity limitations for primary transport are often exceeded to increase the productivity rate per load up to a level of maximum mass payload capacity, a bulk density of 0.375t/m^3 is suggested for primary transport (see Table 28, above).

The forwarding productivity or cycle length of the forwarder was also derived from Industrial Production Standards (Forestry Solutions, 2007f) taking the average lead distance (501-600m), slope conditions (7-20%), ground conditions (moderate) and ground roughness (uneven) into account. This results in a cycle length of 42 minutes or 1.43 cycles per hour. Hence, around 12t/h of the whole-tree biomass is forwarded to the roadside when using a forwarder.

A purchase price of R2.9 million for the forwarder, plus R145 000 for spares, an economic lifetime expectancy of 15 000PMH, a salvage value of 10% of the purchase price, fixed costs (licence and insurance), and variable costs (fuel consumption of 23l/PMH, and repairs and maintenance costs of R232/PMH, etc.) result in a machinery cost of R529/PMH. Adding operator costs of R56.36/h gives a total of R585.40 per hour, translating into forwarding costs of R49 per tonne for harvesting system I.

Since no complete forwarder dataset for the LCA was available, an agricultural combine harvester dataset was modified according to the forwarder specifications.

5.3.2 Harvesting system II

LBSs 9-16 envisage motor-manual harvesting, i.e. felling, de-branching, topping and cross-cutting into two logs per stem, leaving the branches and tops behind, followed by biomass extraction with a tractor coupled to a modified trailer, with a delay of several weeks for air-drying. With logs, the ease of handling improves significantly, and this harvesting system accommodates manual loading and unloading of the feedstock, resulting in increased job opportunities, particularly in the low-income sector.

Similar to the 'felling-only' operation above, the productivity rates for chainsaw operation were derived, assuming best operating practices, from industrial production standards (Forestry Solutions, 2007a), resulting in a productivity rate of 26 trees per hour. The average cost per PMH is the same as for the 'felling-only' application (R37.80/h, or R68.04/PMH). This motor-manual harvesting application is considerably more expensive due to its lower efficiency, as shown per biomass procurement area in Table 29, below. Forwarding using agricultural machinery entails using a 67kW, four-wheel drive, high-power-demand tractor coupled with a modified pole-trailer. Based on a cycle length of 50 minutes per load (Forestry Solutions, 2007b), assuming the same forwarding conditions as for the forwarder mentioned above, and a maximum load capacity of 10 tonnes ($30m^3$), around 12t/h are extracted with the tractor-trailer combination.

Purchase prices of R411 369 for the tractor and of R270 000 for the trailer, both of which have an economic lifetime expectancy of 12 000PMH, were derived from the *Guide to Machinery Costs* (Lubbe et al., 2011). Based on the assumptions of fixed and variable costs made in the guide, the total tractor-trailer combination cost per PMH was calculated at R269.80, translating into a per ton cost of R22.48 (logs, 40% MC).

The above-stated tractor specifications and the production-related emissions were taken into account in the LCA by modifying the 'universal tractor' dataset provided in the Gabi database (PE International, 2006).

Table 29: Harvesting system II – productivity rate and costs per hectare for each BPA (2011)

Biomass procurement area (BPA)		**BPA I**	**BPA II**	**BPA III**	**BPA IV**
Stems per hectare (SPH)		2 000	2 200	1 800	1 250
Logs per hectare		4 000	4 400	3 600	2 500
Yield/rotation	t/ha (80% MC, whole tree)	135	126	90	75
	t/ha (40% MC, logs) [a]	74	69	49	41
Motor-manual harvesting	Productivity (trees/hour) [b]	26			
	Time (h/ha)	77	85	69	48
	Productivity (t/h)	0.96	0.82	0.71	0.85
	Cost (R/ha)	R2 908	R3 198	R2 617	R1 817
Manual loading and unloading	Loading (trees/worker/hour) [c]	38			
	Unloading (trees/worker/hour) [d]	76			
	Loading time/area unit (h/ha)	106	116	95	66
	Unloading time/area unit (h/ha)	53	58	47	33
	Total time (h/ha)	159	174	142	99
	Cost (R/ha) [f]	R1 072	R1 173	R957	R667
Forwarding with tractor-trailer combination	Max. payload capacity	10t/load (30m^3/load)			
	Bulk density (logs)	0.67			
	Cycle length (min) [g]	50			
	Load capacity (t/h)	12			
	Time (PMH/ha)	6.2	5.8	4.1	3.5
	Cost (R/ha)	R1 653	R1 542	R1 102	R925
Cost (R/t)	Harvesting	R71	R83	R96	R80
	(Un)loading	R14	R17	R20	R16
	Forwarding	R22	R22	R22	R22
	Total	R108	R122	R138	R119

Notes:

[a] 30% of biomass (branches, tops, etc.) remains in-field unutilised.

[b] Motor-manual harvesting (felling, debranching, topping and cross-cutting) derived from Industrial Production Standards (Forestry Solutions, 2007a).

[c] Manual loading derived from Industrial Production Standards (Forestry Solutions, 2007d), assuming a team of six workers (2 040 trees/shift).

[d] For unloading, half of the loading time was assumed.

[e] Assuming the agricultural minimum wage of R6.74/hour.

[f] Forwarding cycle length derived from Industrial Production Standards (Forestry Solutions, 2007b).

Based on Forestry Solution's Industrial Production Standards for the manual loading of logs, a team of six workers, with four loading and two positioning on the transportation unit, was assumed (Forestry Solutions, 2007d). Taking log volume, time after felling, ground conditions, and carrying distance into account, a team is expected to load 2 040 logs per workday, resulting in 38 logs/worker/hour. For unloading, a productivity rate of double that for loading was assumed.

5.3.3 Harvesting system III

Harvesting system III (LBSs 17-24) represents a fully mechanised application, using modified forestry machinery for both harvesting and forwarding. A variety of companies specialising in dedicated forestry machinery (such as John Deere/Timberjack, Valmet, Ponsse, Tigercat, Caterpillar, Logset, Konrad, Bell Equipment, to name a few) have developed harvester configurations well suited for small-tree harvesting.

For this study, machinery from a local manufacturer was selected, namely, the Bell Equipment Ultra C disc feller-buncher (see Figure 27, below), with a net engine power of 82.5kW, an operating weight of 7 950kg, and a maximum cutting diameter of 46cm. While other harvesting systems allow felling, de-branching, topping, cross-cutting, and in some cases, also de-barking, and are more commonly used for timber or pulp wood harvesting, tricycle or articulated rubber-tyred drive-to-tree feller-bunchers only fell trees and bunch them next to the skidding track. This represents by far the cheapest commercially available machine for this type of operation (Seixas et al., 2006). They are also advantageous as the felled trees can be left in-field for air-drying and to leave foliage behind, resulting in reduced nutrient loss.

Figure 27: BELL Equipment's Ultra C disc feller buncher

The productivity rate extrapolated from the guidelines for best operating practices for harvesting with a feller-buncher is assumed to be 240 trees per hour, resulting in an average across all four biomass procurement areas of 14.1 tonnes per hour (Forestry Solutions, 2007c). Table 30, below, shows for each BPA the respective productivity rates (in h/ha and t/h).

Table 30: Harvesting system III – productivity rate and costs per hectare for each BPA (2011)

Biomass procurement area (BPA)		**BPA I**	**BPA II**	**BPA III**	**BPA IV**
Stems per hectare		2 000	2 200	1 800	1 250
Yield/rotation (t/ha, 80% MC)		135	126	90	75
Yield/rotation (t/ha, 40% MC)		105	98	70	59
Harvesting: feller-buncher [a]	Productivity (trees/hour) [b]	240	240	240	240
	Time (PMH/ha)	8.3	9.2	7.5	5.2
	Productivity (t/h)	16.2	13.8	12.0	14.4
		R2 644	R2 931	R2 389	R1 657
Extraction with forwarder [c]	Max. payload capacity	14t/load (22.40m^3/load)			
	Bulk density (logs)	0.375			
	Cycle length (min) [d]	42			
	Productivity (t/h)	12			
	Time (PMH/ha)	8.75	8.17	5.83	4.92
	Cost (R/ha)	R5 122	R4 781	R3 415	R2 878
Cost (R/t)	Feller-buncher	R20	R23	R27	R22
	Forwarder	R49	R49	R49	R49
	Biomass at roadside	R68	R72	R75	R71

Notes:
[a] Bell Equipment Ultra C disc feller-buncher.
[b] Harvesting productivity extrapolated from Industrial Production Standards (Forestry Solutions, 2007c).
[c] Forwarder John Deere/Timberjack 1410D.
[d] Forwarding productivity derived from Industrial Production Standards (Forestry Solutions, 2007f).

The capital investment cost quoted for this machine is R1.7 million, and it has an economic lifetime expectancy of 20 000PMH. A fixed cost of R83/PMH, taking *inter alia* licence, insurance and depreciation into account, plus variable costs of R180/PMH (including repairs and maintenance, as well as fuel costs of R120/PMH), less a salvage value, results in a total machinery cost of R262 per productive machine hour. With harvester operator costs of R56/PMH, the total costs are set at R319/PMH.

The same financial, productivity and LCA-relevant data for the John Deere/Timberjack 1410D forwarder specified for HS I are proposed.

5.3.4 Harvesting system IV

LBSs 25-32 comprise harvesting with a feller-buncher and forwarding with a tractor-pole trailer combination. Additional machinery is required for the loading and unloading of the whole tree biomass, since harvesting with a feller-buncher accommodates only the felling operations, and the agricultural machinery is not fitted with a crane for loading/unloading. Commonly used for loading in South African forestry is the three-wheeler loader (e.g. Bell Equipment 220A telelogger) as shown in Figure 28, below.

The so-called ‘three-wheeler’ is a South African invention characterised by its high mobility and manoeuvrability, but it is limited by its carry load capacity. Other disadvantages of the machine are that it cannot build high stacks or handle long lengths (Langenhoven, 2000).

The feller-buncher dataset deployed for HS III, as well as the tractor-pole trailer dataset from HS I also apply to this harvesting system, though the forwarding differs concerning the assumed bulk density. As for HS I, the whole-tree bulk density for primary transport is assumed to be 0.375t/m^3. However, the mass capacity is limited to 10t/load so that the volumetric capacity limitation of 30m^3 will not be reached.

The Bell Equipment 220A Telelogger is powered with a 49kW engine, has an operating weight of 5 100kg and can grab up to 0.35m^3. The average fuel consumption according to the Guide to Machinery Costs (Lubbe et al., 2011) is estimated at 7 litres per hour. The intermediate capital investment cost of R495 000, together with fixed and variable costs, result in a total machinery cost of R162.43 per hour. Adding R25.62/h for operator costs gives a total of R188.05 per hour.

Figure 28: Bell Equipment’s 220A Telelogger

Derived from the industrial standards for loading with a three-wheeler loader (Forestry Solutions, 2007e), the three-wheeler loads 65 trees per hour, taking variables such as time after felling (six weeks), average lead distance (11-20m), moderate landing conditions, and uneven ground roughness into consideration. 200% efficiency gain is assumed for unloading.

Table 31: Harvesting system IV – productivity rate and costs per hectare for each BPA (2011)

Biomass procurement area (BPA)		**BPA I**	**BPA II**	**BPA III**	**BPA IV**
Stems per hectare		2 000	2 200	1 800	1 250
Yield/rotation (t/ha, 80% MC)		135	126	90	75
Yield/rotation (t/ha, 40% MC)		105	98	70	59
Harvesting: feller buncher [a]	Productivity (trees/hour) [b]	240	240	240	240
	Time (PMH/ha)	8.3	9.2	7.5	5.2
	Productivity (t/h)	16.2	13.8	12.0	14.4
	Cost (R/ha)	R2 644	R2 931	R2 389	R1 657
Three-wheeler loader [c]	Loading (trees/hour) [d]	98	98	98	98
	Unloading (trees/hour) [e]	196	196	196	196
	Time (h/ha)	31	34	28	19
	t/h	3.43	2.91	2.54	3.08
Forwarding with tractor-trailer combination	Max. payload capacity	10t/load (30m^3/load)			
	Bulk density (whole tree)	0.375			
	Cycle length (min) [f]	50			
	Load capacity (t/h)	12			
	Time (PMH/ha)	6.2	5.8	4.1	3.5
	Cost (R/ha)	R1 653	R1 542	R1 102	R925
Cost (R/t)	Feller-buncher	R16	R19	R22	R18
	Tractor-trailer	R21	R21	R21	R21
	Loading/Unloading with three-wheeler	R55	R65	R74	R 61
	Biomass at roadside	R92	R105	R117	R100

Notes:

[a] Bell Equipment Ultra C disc feller-buncher.
[b] Harvesting productivity extrapolated from the Industrial Production Standards for feller-buncher harvesting (Forestry Solutions, 2007c).
[c] Bell Equipment 220A Telelogger.
[d] Three-wheeler loading productivity derived from Industrial Production Standards (Forestry Solutions, 2007e).
[e] Unloading assumed to be twice as efficient as loading.
[f] Forwarding cycle length derived from Industrial Production Standards (Forestry Solutions, 2007b).

5.3.5 Harvesting system V

Unlike the aforementioned harvesting systems, which have their origin in conventional forestry applications, harvesting system V has its roots in agriculture. A modified self-propelled forage harvester fitted with a dedicated biomass harvesting head cuts and chips the SRC crop in a single operation, simultaneously blowing the comminuted biomass into a container-trailer coupled to a tractor. Figure 29**,** below, is a schematic illustration of such a biomass harvesting head (Fiala and Bacenetti, 2011: 2).

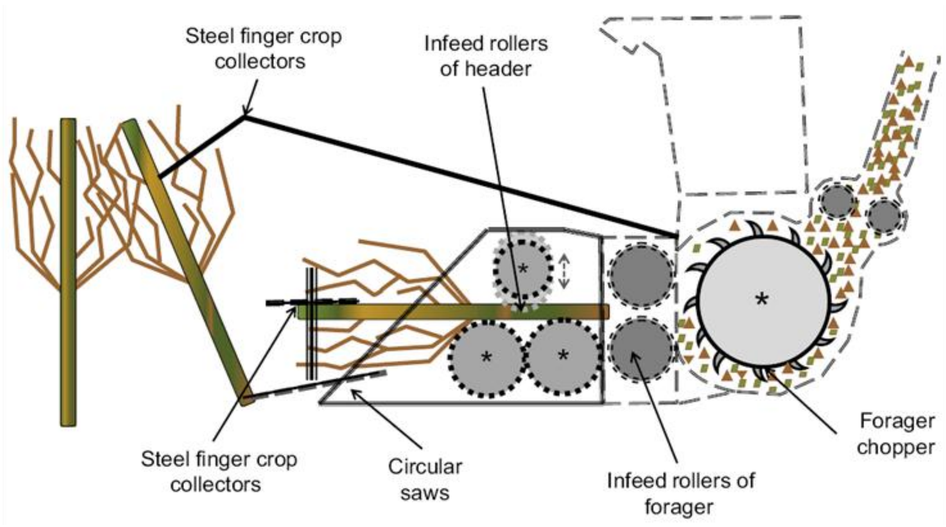

Figure 29: Schematic illustration of a dedicated SRC biomass harvesting head fitted to front of a self-propelled forage harvester

Source: Fiala and Bacenetti (2011: 2)

For this study, the GBE2 header coupled with the Claas Jaguar 880 forage harvester was assumed. This system can work with trees with a basal diameter of about 12-14cm, more than that managed by other headers on the market. After being cut, shoots are sent to the forage chipper. The header – 2.5m wide, 2.7m long and 1.4m high, with a mass of 2 050kg – receives its power from the self-propelled harvester (engine power = 343kW) via cardanic joint (Fiala and Bacenetti, 2011). The system can harvest up to 50 tonnes per hour consuming 40-50 litres per hour. A productivity of 35/h with a fuel consumption of 40l/h was assumed.

With a combined purchase price for the harvester and biomass harvesting heads of R3.11 million, less a salvage value of 10%, plus licence and insurance costs, as well as variable costs, such as repairs and maintenance and fuel consumption, result in a production cost of R2 167/PMH. Based on a salary of R10 568 per month, the operator cost is R56.36/PMH. Hence, the total cut-and-chip harvesting costs add up to R2 224/PMH.

Primary transport costs of R197/PMH for a tractor (67kW, four-wheel drive, high-power demand) and a container-trailer with a capacity of 30m^3, derived from the Guide to Machinery database (Lubbe et al., 2011) were also taken into account. Added to this are R26/h for tractor operator costs, resulting in an operating cost of R267/PMH for the primary transport operation. At least two forwarding tractor-trailor combinations are required to ensure a continuous harvest with the combine harvester transporting the comminuted biomass from in-field to roadside.

Table 32: Harvesting system IV – productivity rate and costs per hectare for each BPA (2011)

Biomass procurement area (BPA)		**BPA I**	**BPA II**	**BPA III**	**BPA IV**
Stems per hectare		2 000	2 200	1 800	1 250
Yield/rotation (t/ha, 80% MC)		135	126	90	75
Harvesting: feller buncher [a]	Productivity (t/h)[1]	35	35	35	35
	Time (PMH/ha)	3.9	3.6	2.6	2.2
	Cost (R/ha)	R8 577	R8 006	R5 718	R4 765
Forwarding with tractor-container trailer combination	Max. payload capacity	$30m^3$/load			
	Bulk density [b]	0.51			
	Time (PMH/ha)	3.9	3.6	2.6	2.2
	Cost (R/ha)	R2 062	R1 924	R1 374	R1 145
Cost (R/t)	Cut-and chip harvester	R64	R64	R64	R64
	Tractor-container trailer	R15	R15	R15	R15
	Biomass at roadside	R79	R79	R79	R79

Notes:
[a] Productivity varies between 35-50t/h, depending on wood density (Nardin, 2009).
[b] For fresh, comminuted whole-tree biomass (80% MC dry basis).

For the LCA, the 'universal tractor' provided in the GaBi database was modified according to the above-stated specifications (PE International, 2006). Similarly, relevant data was changed for the corn harvesting process to meet the specifications of the modified combine harvester.

5.4 Biomass comminution

As briefly discussed in section 4.3.1.3, two locations for biomass comminution are proposed, i.e. mobile comminution at the roadside and stationary comminution at the landing of the central conversion plant.

5.4.1 Mobile comminution at roadside

In the case of mobile comminution at the roadside, the biomass is fed manually into the chipping system, and the chipped biomass is simultaneously blown into a container. This system is characterised by its flexibility and mobility, and offers great employment potential, particularly in the low-skills segment. However, low productivity results in low cost efficiency.

For mobile roadside comminution, the Danish-made Lindana TP 200 PTO wood chipper was selected. This all-round wood chipper, characterised by its functionality and flexibility, is mounted onto and driven by tractor (e.g. the above-mentioned 67kW, four-wheel drive, high-power demand tractor). The disc chipper, equipped with a hydraulic feed, three chipping knives and three anvils, can be fed with trees of up to 200mm in diameter, resulting in a hardwood chipping capacity of 6-$10m^3$/hour (12-$18m^3$/h for softwood). For this study, a chipping capacity of 5.0t/PMH for whole trees and 6.7t/PMH for logs was proposed, assuming a biomass moisture content of 40% (dry basis) and a wood density of 720kg/m^3. During the chipping operation a fuel consumption of 6-8l/h is expected, using a conservative consumption of conservative 8l/PMH for the financial and LCA calculations.

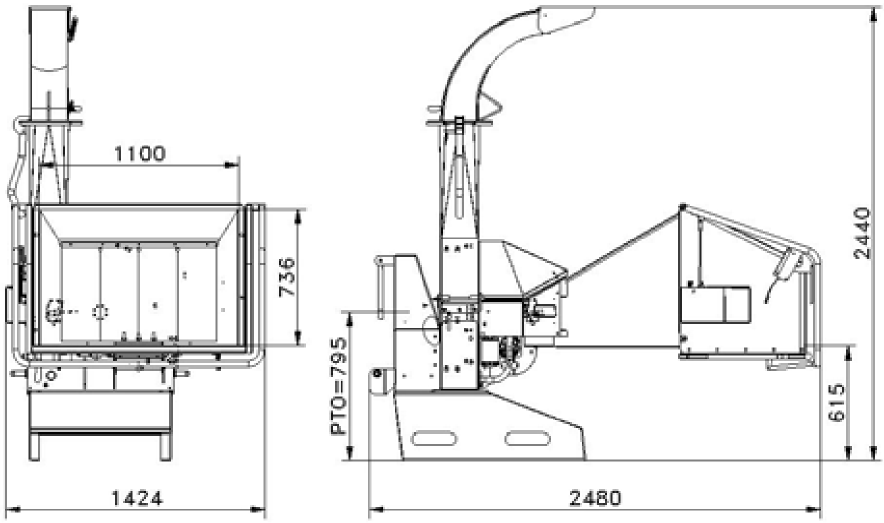

Figure 30: Technical drawing of Lindana TP 200 PTO wood chipper

The cost price for the 700kg heavy equipment is R155 000, with an economic lifetime expectancy of 20 000PMH. An annual cost of R24 492 for spares such as chipping knives, square wipers and hydraulic filters needs to be added to the financial assessment, assuming an annual usage of 2 000PMH. The costs for the tractor driving the chipper are R411 369 based on the Guide to Machinery Costs (Lubbe et al., 2011). Taking fixed and variable costs for the whole chipping system into account, the machinery cost adds up to R264/PMH. To ensure a continuous biomass feed into the chipper, one tractor operator, as well as five workers for manual feeding are taken into account, resulting in labour costs of R59/PMH. A total production cost of R323/PMH translates into R65/t for chipping whole trees and R49/t for logs.

Similar to the processes in the life cycle prior to comminution, the 'universal tractor' from the GaBi database (PE International, 2006) has been modified to meet the specifications stated above. Based on Jungmeier et al. (2003), a 5% material loss of biomass during mobile comminution and transport was stipulated for feedstock and energy loss, assuming natural decomposition of these losses over time.

5.4.2 Stationary comminution at landing of central conversion plant

Generally, compared with a mobile system, a stationary chipping line is characterised by significantly higher capital investment costs but also by its greater chipping capacity, resulting in lower unit production costs (R/t).

Assuming the same biomass properties for chipping as stated above, the *Maier drum chipper HRL 1200/ 450 x 1000 – 8EW* stationary chipping line caters for biomass of up to 160mm, producing chips of 30-35mm (Rahlmeyer, 2011). Incorporating potential downtimes for maintenance and repairs, an average chipping capacity for logs of around 16.8t/h and 12.6 for whole trees (40% MC, dry basis) was assumed, although potentially up to 28t can be processed hourly.

The capital investment costs, fixed costs, and variable costs of the stationary chipping line are listed in Table 33, below. Assuming a capacity of 17t/h for logs and 13t/h for chipping whole tree biomass, the total comminution costs per tonne add up to R36 and R42 respectively.

The electrical energy consumption of the whole chipping line is 20-25kW per tonne of produced chips. The required electricity is assumed to be provided by the national electricity supplier ESKOM at a tariff of R0.75 per kWh. Maintaining the computer-controlled system requires one qualified engineer for supervision, and a technician. Concerning material losses during transport and comminution, a similar approach to that for mobile comminution was used, i.e. 2% of the biomass was specified for feedstock and energy loss.

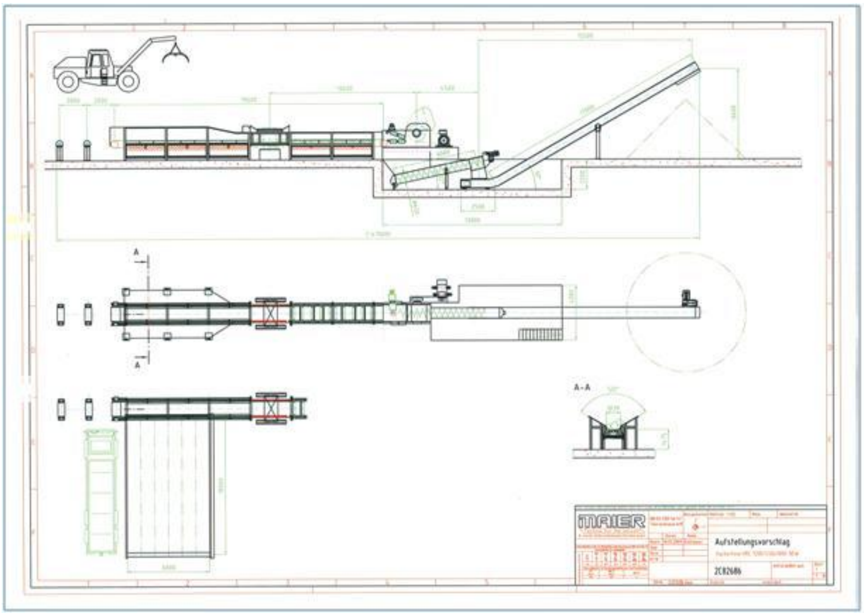

Figure 31: Stationary chipping line Maier drum chipper HRL 1200/ 450 x 1000 – 8EW

as proposed by German-based Maier company (Rahlmeyer, 2011)

Table 33: 'Maier drum chipper HRL 1200/ 450 x 1000 – 8EW' drum chipper feeding line (2011)

Designation	**Unit price (€)**	**Unit price (ZAR)** [a]	**ELE** [b] **(years)**	**Qty.** [c]	**Annualised costs (ZAR/a)** [d]	**Cost per hour (ZAR/h)**
Fixed costs:						
Chipper feeding line	110 000	1 227 600	20	1	61 380	15.35
Storage cross chain conveyor	180 000	2 008 800	20	1	100 440	25.11
MAIER drum chipper HRL 1200/450x1000 – 8EW[1]	250 000	2 790 000	20	1	139 500	34.88
Discharge screw	35 000	390 600	20	1	19 530	4.88
L-shaped trough chain conveyor	50 000	558 000	20	1	27 900	6.98
Installation cost	50 000	558 000	20	1	27 900	6.98
Variable costs:						
Spare and wear parts for chipping unit	30 000	334 800	1	1	334 800	83.70
Spare and wear parts for conveyor units	5 000	55 800	2	2	55 800	6.98
Maintenance (3% of capital investment)	187 500	2 092 500	20	1	104 625	26.16
Labour (1x engineer/1x qualified technician)		450 000	1	1	450 000	112.50
Sum:					**1 293 975**	**323.49**

Energy (22kW/t produced chips) [e]	Feedstock type	Chipping capacity (t/h)	Energy required (kWh)	Cost per hour (R) [f]
	Logs	16.8	369.6	277.20
	Whole trees	12.6	277.2	207.90

Unit cost	Feedstock type	Total cost per hour (R/h)	Unit cost (R/t) [g]
	Logs	600.69	35.76
	Whole trees	531.39	42.17

Source: Rahlmeyer (2011)

Notes:

[a] Assuming an exchange rate of R11.16 to the Euro.
[b] Economic Lifetime Expectancy (ELE).
[c] Quantity (Qty).
[d] Based on 250 working days with two shifts of 8 hours each.
[e] Energy consumption of whole chipping line is 20-25kW/t produced chips.
[f] Assuming an electricity tariff of R0.75/kWh and an energy supply from the national grid.
[g] Based on 40% moisture content (dry basis).

5.5 Thermal pretreatment

Both the location of the stored biomass and the shape of the biomass (comminuted or uncomminuted) depend on the harvesting system applied. In the case of harvesting systems I-IV, uncomminuted biomass is stored in-field to air dry for several weeks until the biomass has reached moisture content levels of around 40% (dry basis). Once this level has been reached, the biomass is forwarded to the roadside for further processing. In the case of harvesting system V, the trees are felled and comminuted in a single process, resulting in wood chips with moisture content levels of around 80% (dry basis).

Irrespective of whether the biomass has been air-dried in-field prior to comminution or not, additional drying is required to meet the moisture content requirements of the respective conversion technologies, i.e. the MC levels need to be further reduced to at minimum less than 20% (dry basis). This can be achieved by additional air-drying in a storage system such as the relatively inexpensive so-called dome-aeration-technology (Grosse, 2008) and/or by using the exhaust heat from the conversion process in a conveyor belt drier, a drum drier, chamber, or container drier.

However, for all 37 LBSs, the assumption was made that by using the exhaust heat of the respective conversion system, no additional energy would be required to reach the stipulated moisture content levels of the bioenergy feedstock. Hence, no additional costs and emissions arise from the active drying processes.

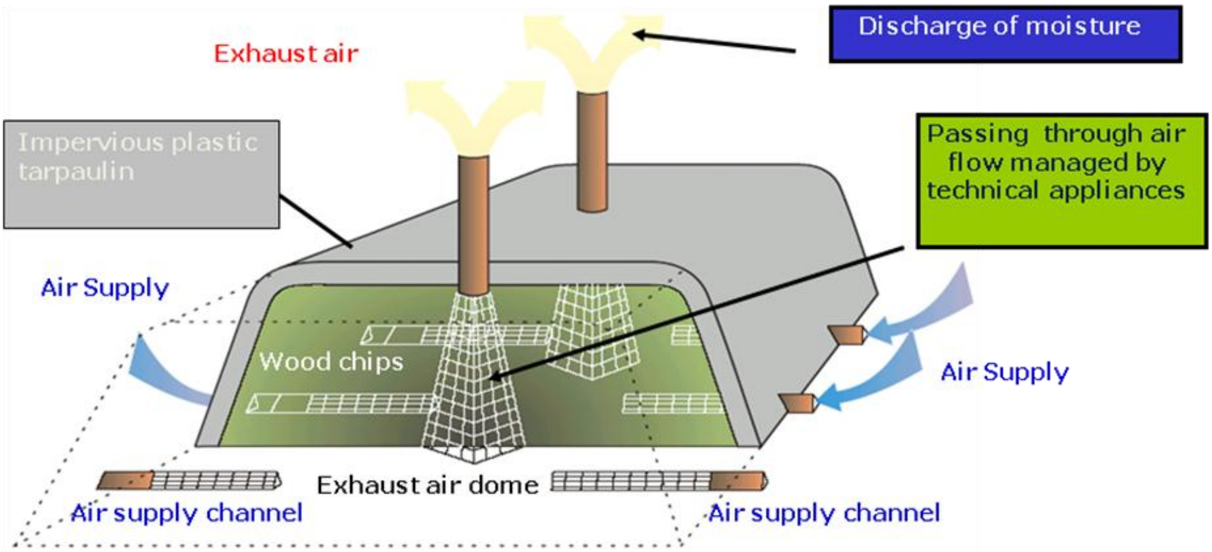

Figure 32:Dome-Aeration Technology

Source: Brummack and Bartha (2005); Trois and Polster (2007)

5.6 Mobile fast pyrolysis

Pyrolysis entails the thermal degradation of biomass in the absence of an oxidising agent, whereby the volatile components of a solid carbonaceous feedstock are vaporised in primary reactions by heating, leaving a residue consisting of char and ash. Pyrolysis always produces a gas vapour that can be collected as a liquid and a solid char. Fast-pyrolysis processes are designed and operated to maximise the liquid fraction by up to 75%wt on a dry-biomass feed basis (Bridgwater et al., 2001).

Although fast-pyrolysis can be understood as some form of pretreatment of the biomass, it also represents one of the possible pathways for upgrading low-bulk-density biomass into densified, more homogeneous energy carriers. Hence, detailed information on the application of this technology can be found in section 5.8, which deals with generating bioenergy. Section 5.8.6 discusses the application of a centralised, stationary fast-pyrolysis system, whereas sections 5.8.7-8 are concerned with a mobile/portable configuration for fast-pyrolysis.

5.7 Secondary transport of bioenergy feedstock

Table 34: Various types of HCVs for secondary transport of bioenergy feedstocks

Commodity to be transported (h/load)	Uncomminuted biomass		Comminuted biomass		Mobile fast pyrolysis	
	Whole tree	**logs/ stemwood**	**Whole tree**	**logs/ stemwood**	**bio-oil**	**bio-char**
Bulk density (t/m^3)	0.20	0.67	0.33 (0.51) [b]	0.40	1.20	0.5
Truck configuration [a]	c	c	d	d	e	d
Trailer type	Pole	Pole	Container	Container	tanker	Container
Max. permissible combination mass (t)	49.5	49.5	56.0	56.0	49.5	56.0
Payload capacity (t)	31.98	31.98	38.48	38.48	31.98	38.48
Payload capacity (m^3)	160	160	114	114	20	114
Limitation due to	Mass	Mass	Volume	Mass	Volume	Mass
Effective payload capacity (t)	31.98	31.98	37.68	38.48	24	38.48

Notes:

[a] Based on assumptions made by Roberts (2009: 77) using the Road Freight Association's Vehicle Cost Schedule (RFA, 2009).
[b] In the case of harvesting system V fresh biomass (80% moisture content) is to be transported.
[c] Six-axle articulated vehicle.
[d] Seven-axle articulated vehicle.
[e] Five-axle articulated vehicle.

Three truck configurations (or heavy commercial vehicles, HCV) were selected for transporting the bioenergy feedstocks. When transporting uncomminuted biomass, a six-axle articulated vehicle fitted with a pole-trailer (payload capacity of 31.98t or 160m^3), and a seven-axle articulated vehicle capable of transporting three containers, with a total payload capacity of 114m^3 (54t), were assumed for transporting comminuted biomass or bio-char. Bio-oil from a mobile fast-pyrolysis system needs to be transported in a different truck configuration, i.e. in a dedicated truck-tanker configuration characterised by a volume capacity of 20 000 litres. Based on a bulk density of 1.2t/m^3 for bio-oil, up to 24 tonnes can be transported per load.

Determining the mass transport rate, the following additional assumption has been made: in all cases, the trucks must complete a whole number of round trips from the central conversion plant to the roadside where the commodity is to be procured and back in a nine-hour day.

Table 35, below, shows the assumed fixed time requirements, i.e. the time per load required, irrespective of the time needed for travelling. This includes the loading and securing of the load prior to travelling, and once the destination has been reached, the clearing of the load, i.e. unloading and weighing prior to and after unloading. Since the fixed time requirements for transporting uncomminuted whole trees and log/stemwood for the selected tree species were not available, the values used were extrapolated from data pertaining to the transportation of uncomminuted whole trees provided by Ranta and Rinne (2006), and for logs/stemwood by Forestry Solutions (2007e). Further research in this matter is recommended. The total fixed time requirements for transporting whole trees is estimated at 3.15 hours, and for logs/stemwood, 2.82 hours. In the case of transporting comminuted biomass, a total fixed time of 1.25h was assumed. Similarly, 1.25h are required for bio-char and 1.17h for bio-oil. The fixed time assumed for the latter was derived from Rogers and Brammer (2009: 1370).

Table 35: Fixed time requirements for loading, unloading, securing and weighing (in h/load)

Commodity to be transported	**Uncomminuted biomass**		**Comminuted biomass** [d]		**Mobile fast pyrolysis**	
	whole tree [b]	logs/ stemwood [c]	whole tree	logs/ stemwood [c]	bio-oil [e]	bio-char [f]
Loading	1.52	1.36	0.75	0.75	0.50	0.75
Securing of load	0.22	0.20	0.17	0.17	0.07	0.17
Weighing [a] and unloading	1.41	1.26	0.33	0.33	0.60	0.33
Total fixed time requirements	3.15	2.82	1.25	1.25	1.17	1.25

Notes:

[a] Weighing of truck prior to and after unloading.
[b] Extrapolated from Ranta and Rinne (2006: 233).
[c] Extrapolated from Forestry Solutions (2007e).
[d] Fixed time requirements for comminuted biomass derived from Rogers and Brammer (2009: 1368) and Badger (2002).
[e] The required fixed time for bio-oil was also derived from Rogers and Brammer (2009: 1370).
[f] The same fixed time requirements as for comminuted biomass were assumed.

Bio-oil typically has a density of 1 200kg/m^3, so the truck's load will be limited by its weight. Much research has been done on the nature of bio-oil, possible commercial standards for bio-oil, its storage, and handling characteristics (Bridgwater, 2011; Oasmaa et al., 2010; Venderbosch and Prins, 2010; Zhang et al., 2010; Czernik and Bridgewater, 2004; Huffman et al., 1993). The pH, viscosity, high density, poor miscibility and aging characteristics mean that dedicated tankers are needed for bio-oil (Rogers and Brammer, 2009: 1370). It has been proposed that bio-oil be moved by gravity from delivery tankers into a reception well (Badger and Fransham, 2006). In this situation the unloading time will be governed by the viscosity of the bio-oil and the dimensions of the unloading pipe. The Hagen Poiseuille law governs the flow of Newtonian liquids through pipes:

Equation 11: The Hagen-Poiseuille law

$$Flow = \frac{\pi P r^4}{8\eta l}$$

Where P is the pressure, r is the radius of the pipe, η is the viscosity and l is the length of the pipe. If typical figures are taken from the Dynamotive bio-oil data sheet (Dynamotive Energy Systems, 2011), with a temperature of 40°C, a loading head of 5m, a pipe length of 2m and six parallel 200mm diameter loading pipes, a 28t payload tanker could be loaded in 15 minutes. If allowance is made for connecting and disconnecting hoses, this will lead to a loading time of the order of 30 minutes (Rogers and Brammer, 2009). If it is assumed that the unloading time is the same as the truck loading time and a 10 minute allowance is made for weighbridge operations, the non-driving time per round trip will be 70 minutes. This figure has been used to calculate the travelling time for bio-oil.

As mentioned in Section 2.3, above, 14 demand points/biomass procurement areas were identified based on various considerations, such as proximity of electricity substations and major grid lines; proximity of industrial consumers in order to sell excess heat/thermal energy produced in the conversion process as a by-product; and proximity to the road network, to ease feedstock transport and to avoid the additional costs of infrastructure; as well as the projected electricity demand in the CWDM (Roberts, 2009: 50-58). Four demand points, Paarl, Worcester, Ashton and the Rural Cederberge, were selected for further assessment, *inter alia*, based on the respective biomass productivity levels in each biomass procurement area (relatively high, medium, medium-low, and low – see section 4.3.2) and spatial distribution within the CWDM. The first three demand points are characterised by their proximity to infrastructure in terms of road network, electricity lines and electricity substations, as well as to industrial consumers interested in using thermal energy for production. The Rural Cederberge demand point, on the other hand, is characterised by its remoteness and its lack of scope for additional income from selling excess heat/thermal energy, since no industrial consumers are located in the vicinity. Also, additional investments in electricity infrastructure are required to supply electricity to the grid.

The average transport distance for each demand point is a function of the supply and demand of bioenergy feedstock. The supply depends, *inter alia*, on the availability of land for biomass production, the willingness of landowners to participate by offering their land for lignocellulosic-biomass production and the productivity rate of the respective areas. The demand component is mainly driven by the conversion efficiency of the respective bioenergy system, but also by feedstock losses during the procurement and pretreatment of the feedstock.

Biomass productivity and land availability in the CWDM were determined by Von Doderer (2009) using geographic information systems (GIS) and were further assessed by Roberts (2009) in a transport optimisation model using GIS and LINGO, where various landowner participation levels were assessed. For this study, a participation level of 50% was assumed for landowners.

The feedstock demand, i.e. the biomass required to ensure a supply for continuously generating 5MW electricity, is mainly driven by the conversion efficiency of the respective bioenergy system. However, due to losses of biomass in the value chain prior to the conversion, more biomass needs to be produced than is used in the conversion process. Biomass losses, and therefore energy feedstock losses, occur for instance in-field, where only logs are used further in the process (less 30% of the fresh biomass), as is the case for LBSs 9-16, or in a one-pass harvesting system (as is the case for LBSs 33-37), where biomass is harvested and comminuted in a single operation, resulting in a loss of 5% of fresh biomass. The same quantity of loss of biomass (5% at 40% moisture content) is assumed when comminuting biomass at the roadside, as is assumed in a generic biomass comminution dataset provided in the GaBi database (PE International, 2006). Since greater capacity and efficiency are assumed for stationary comminution at the landing of the central conversion plant, a biomass feedstock loss of 2% (at 40% moisture content) was adopted for the LBSs using stationary comminution. Table 36**,** below, illustrates the mass flow of biomass and pyrolysis products over the life-cycle of each respective lignocellulosic bioenergy system (LBS).

Table 36: Biomass and pyrolysis products mass flow

Location	Plantation/in-field				Roadside		Road	Central conversion plant			
No.	**Biomass (BM) prior to harvesting (t/a)**	**Harvesting**	**Biomass at forwarding (t/a)**	**For-war-ding**	**Pretreatment**	**Secondary transport**	**Bioenergy Feedstock for secondary transport (t/a)**	**Pretreatment**	**Electricity generation**	**BM required for conversion (t/a)**	**BM required for conversion at 80% MC**
1	64 729	$HMM_{wh.\ tree}$ (-40% MC)	50 345[a]	FFM	COMR (-5% BM)	TCB_{40}	47 828		CCB	40 995[c]	61 493
2	55 722		43 339[a]				41 172		CGB	35 291[c]	52 937
3	91 865		71 451[a]				67 878	CPC	CCP	53 333[d]	87 272
4	78 754		61 253[a]		CPM	TPP	22 860/ 12469		CCP	45 721[d]	74 816
5	103 966		80 863[a]				30 179/ 16 461		CGP	60 358[d]	98 768
6	62 748		48 804[a]			TUB_{40}	48 804	COML (-2% BM)	CCB	40 995[c]	61493
7	54 016		42 013[a]				42 013		CGB	35 291[c]	52 937
8	89 053		69 264[a]				69 264	CPC	CCP	53 333[d]	87 272
9	92 471	HMM_{log} (-40% MC, -30% BM remaining in-field)	50 345[a]	FAM_{log}	COMR (-5% BM)	TCB_{40}	47 828		CCB	40 995[c]	61 493
10	79 603		43 339[a]				41 172		CGB	35 291[c]	52 937
11	131 236		71 451[a]				67 878	CPC	CCP	53 333[d]	87 272
12	112 506		61 253[a]		CPM	TPP	22 860/ 12469		CCP	45 721[d]	74 816
13	148 523		80 863[a]				30 179/ 16 461		CGP	60 358[d]	98 768
14	89 640		48 804[a]			TUB_{40}	48 804	COML (-2% BM)	CCB	40 995[c]	61 493
15	77 166		42 013[a]				42 013		CGB	35 291[c]	52 937
16	127 219		69 264[a]				69 264	CPC	CCP	53 333[d]	87 272
17	64 729	HFM (-40% MC)	50 345[a]	FFM	COMR (-5% BM)	TCB_{40}	47 828		CCB	40 995[c]	61 493
18	55 722		43 339[a]				41 172		CGB	35 291[c]	52 937
19	91 865		71 451[a]				67 878	CPC	CCP	53 333[d]	87 272
20	78 754		61 253[a]		CPM	TPP	22 860/ 12469		CCP	45 721[d]	74 816
21	103 966		80 863[a]				30 179/ 16 461		CGP	60 358[d]	98 768
22	62 748		48 804[a]			TUB_{40}	48 804	COML (-2% BM)	CCB	40 995[c]	61 493
23	54 016		42 013[a]				42 013		CGB	35 291[c]	52 937
24	89 053		69 264[a]				69 264	CPC	CCP	53 333[d]	87 272
25	64 729		50 345[a]	$FAM_{wh.\ tree}$	COMR (-5% BM)	TCB_{40}	47 828		CCB	40 995[c]	61 493
26	55 722		43 339[a]				41 172		CGB	35 291[c]	52 937
27	91 865		71 451[a]				67 878	CPC	CCP	53 333[d]	87 272
28	78 754		61 253[a]		CPM	TPP	22 860/ 12469		CCP	45 721[d]	74 816
29	103 966		80 863[a]				30 179/ 16 461		CGP	60 358[d]	98 768
30	62 748		48 804[a]			TUB_{40}	48 804	COML (-2% BM)	CCB	40 995[c]	61 493
31	54 016		42 013[a]				42 013		CGB	35 291[c]	52 937
32	89 053		69 264[a]				69 264	CPC	CCP	53 333[d]	87 272
33	64 729	HAM (-5% BM)	61 493[b]	FAM_{CB}		TCB_{80}	61 493		CCB	40 995[c]	61 493
34	55 722		52 936[b]				52 936		CGB	35 291[c]	52 937
35	91 865		87 272[b]				87272	CPC	CCP	53 333[d]	87 272
36	78 754		74 816[b]		CPM	TPP	22 860/ 12469		CCP	45 721[d]	74 816
37	103 966		98 768[b]				30 179/ 16 461		CGP	60 358[d]	98 768

For notes and explanations of acronyms, please refer to next page.

Notes:

a	40% moisture content (dry basis).
b	80% moisture content (dry basis).
c	20% moisture content (dry basis).
d	10% moisture content (dry basis).
BM	Biomass.
MC	Moisture content.
$HMM_{wh. tree}$	Motor-manual harvesting: felling only.
HMM_{log}	Motor-manual harvesting: felling, de-branching and cross-cutting.
HFM	Harvesting with forestry machinery: whole tree.
HAM	Harvesting with agricultural machinery: whole tree (80% MC; loss of 5% of biomass due to chipping).
FFM	Forwarding of whole trees (40% MC) with forestry machinery: loading/unloading with fitted crane.
FAM_{log}	Forwarding of logs (40% MC) with agricultural machinery: manual loading/unloading.
$FAM_{wh. tree}$	Forwarding of whole trees (40% MC) with agricultural machinery: loading/unloading with three-wheeler.
FAMCB	Forwarding of comminuted biomass (80% MC) with agricultural machinery:
COMR	Mobile comminution at roadside: including loss of 5% BM (40% MC).
COML	Stationary comminution at landing of conversion plant: loss of 2% BM assumed (40% MC).
TUB40	Transport of uncomminuted biomass at 40% MC.
TCB80	Transport of comminuted biomass at 80% MC.
TCB40	Transport of comminuted biomass at 40% MC.
TPP	Transport of pyrolysis products: Bio-oil/bio-char.
CPM	Mobile fast pyrolysis at roadside (10% MC required).
CPC	Stationary fast pyrolysis at central conversion plant (10% MC required).
CCB	Combustion of biomass in integrated boiler-steam turbine system (20% MC required).
CGB	Gasification of biomass in integrated gasifier-gas turbine system (20% MC required)
CCP	Combustion of bio-oil and bio-char in integrated boiler-steam turbine system
CGP	Bio-oil in direct-injection gas turbine/bio-char sold to industrial consumer.

Based on the primary biomass production requirements, which are listed in column 2 of Table 36, above, the weighted average transport distance (WATD) for each demand point and the respective bioenergy conversion system were determined by Van Niekerk (2011) using GIS and FlowMap. Since off-road and on-road transport times and costs differ considerably, road-type factors of 1 for major roads, 1.2 for minor roads, and 1.5 for gravel roads were included to determine average transport distances. Hence, the WATD should be considered to be a relative index of transport and not a true distance. Table 37, below, comprises the WATD for each LBS in relation to the demand points/biomass procurement areas.

The number of truck configurations required to ensure a continuous supply of bioenergy feedstock for each LBS is a function of the number of required shuttle trips from the conversion plant to the roadside and back, the total transport time per load, and the time availability of the truck configuration, as shown in Table 37**,** below. The number of shuttle trips depends on the type and bulk density of bioenergy feedstock to be transported (t/a) and the effective payload capacity (t/load) of the respective truck configuration. The time availability is limited by the working days per year and the shift length per day. As mentioned above, trucks must complete a whole number of shuttle/round trips in a nine-hour working day on 250 working days a year. The total transport time per load encompasses a fixed time component (see Table 36, above) and a variable time component, the travelling time per round trip. The travelling time depends on the WATD, the types of roads used, and the average travelling speed per road type. For this study, 10% of the WATD was allocated for travelling on major roads at an average speed of 82km/h, 40% for minor roads at 70km/h, and for the remainder, an average travelling speed of 27km/h (gravel road and off-road) was assumed. The average speed for the respective road types is based on default values for a EURO 3 Norm, diesel-driven truck from the GaBi database (PE International, 2006). This dataset was also used throughout the LCA model for the related secondary transport inputs and emissions, applying the respective transport distances and masses per load to be transported.

As proposed in Roberts (2009: 59), Concept 11 of the Vehicle Cost Schedule of the Road Freight Association (RFA, 2009) was used to determine the secondary transport costs. The capital investment costs per truck were assumed at R938 875 with a salvage value of 25% and an economic lifetime expectancy (ELE) of 550 000km. Annual insurance and licence costs for the truck are 7.5% of the purchase price and R8 235 respectively. The purchase price for the trailer is R273 719 with a 0% salvage value and an ELE also of 550 000km. The insurance and licence costs for the trailer are 5% of the purchase price and R5 304 respectively. Furthermore, overhead costs (administration and operation) of R135 738 were proposed for Concept 11. The employment costs per truck-trailer combination are R17 680/month for the truck and R6 445/month for an assistant. The total annual fixed costs depend on the annual kilometres driven, which also determine the economic lifetime expectancy in years. The variable costs comprise fuel, lubricants, maintenance and tyres. The fuel consumption was proposed as 55 litres per 100 kilometres. With a diesel price of R10/l, the fuel cost is R5.5/km. Lubricants were specified as 2.5% of the fuel cost. Furthermore, maintenance costs of R1.52/km and R1.05/km for tyre usage were proposed.

Table 37: Number of truck configurations required for secondary transport

No.	Biomass prior to harvesting (t/a at 80% MC)	WATD per BPA[1]				Bioenergy feedstock for secondary transport (t/a)	Type of commodity to be transported	Effective payload capacity (t/load)	No. of shuttle trips required[2]	Total transport time per load (h/load)				Truck configurations required per BPA			
		i	ii	iii	iv					i	ii	iii	iv	i	ii	iii	iv
1	64 729	41	22	15	18	47 828	Comminuted biomass (whole tree$_{40}$)	37.683	1 270	3.3	2.4	2.0	2.2	3	2	2	2
2	55 722	38	21	15	17	41 172		37.683	1 093	3.2	2.3	2.0	2.1	3	2	2	2
3	91 865	49	26	18	23	67 878		37.683	1 802	3.7	2.4	2.2	2.4	4	3	2	3
4	78 754	45	24	17	21	22 860/ 12 469	Bio-oil/ bio-char	24.000/ 38.480	953/ 325	3.5/ 3.5	2.4/ 2.5	2.0/ 2.1	2.2/ 2.3	2/ 1	2/ 1	1/ 1	1/ 1
5	103 966	51	27	19	25	30 179/ 16 461		24.000/ 38.480	1 258/ 428	3.8/ 3.8	2.5/ 2.6	2.1/ 2.2	2.4/ 2.5	3/ 1	2/ 1	2/ 1	2/ 1
6	62 748	41	22	15	18	48 804	Uncomminuted biomass (whole tree$_{40}$)	31.980	1 527	5.2	4.3	3.9	4.1	7	4	4	4
7	54 016	38	21	15	17	42 013		31.980	1 314	5.1	4.2	3.9	4.0	6	3	3	3
8	89 053	49	26	18	23	69 264		31.980	2 166	5.6	4.5	4.1	4.3	9	5	5	5
9	92 471	49	26	18	23	47 828	Comminuted biomass (logs$_{40}$)	38.480	1 269	3.7	2.6	2.2	2.4	3	2	2	2
10	79 603	45	24	17	21	41 172		38.480	1 096	3.5	2.5	2.1	2.3	3	2	2	2
11	131 236	58	29	20	29	67 878		38.480	1 790	4.2	2.7	2.3	2.7	4	3	3	3
12	112 506	53	27	19	27	22 860/ 12 469	Bio-oil/ bio-char	24.000/ 38.480	953/ 325	3.9/ 3.9	2.5/ 2.6	2.1/ 2.2	2.5/ 2.6	2/ 1	2/ 1	1/ 1	2/ 1
13	148 523	60	31	21	33	30 179/ 16 461		24.000/ 38.480	1 258/ 428	4.2/ 4.3	2.7/ 2.7	2.2/ 2.3	2.8/ 2.9	3/ 1	2/ 1	2/ 1	2/ 1
14	89 640	49	26	18	23	48 804	Uncomminuted biomass (logs$_{40}$)	31.980	1 558	5.3	4.1	3.7	4.0	7	4	4	4
15	77 166	45	24	17	21	42 013		31.980	1 314	5.1	4.0	3.7	3.9	6	3	3	3
16	127 219	58	29	20	29	69 264		31.980	2 198	5.8	4.3	3.8	4.3	9	5	5	5
17	64 729	41	22	15	18	47 828	Comminuted biomass (whole tree$_{40}$)	37.683	1 270	3.3	2.4	2.0	2.2	3	2	2	2
18	55 722	38	21	15	17	41 172		37.683	1 093	3.2	2.3	2.0	2.1	3	2	2	2
19	91 865	49	26	18	23	67 878		37.683	1 802	3.7	2.4	2.2	2.4	4	3	2	3
20	78 754	45	24	17	21	22 860/ 12 469	Bio-oil/ bio-char	24.000/ 38.480	953/ 325	3.5/ 3.5	2.4/ 2.5	2.0/ 2.1	2.2/ 2.3	2/ 1	2/ 1	1/ 1	1/ 1
21	103 966	51	27	19	25	30 179/ 16 461		24.000/ 38.480	1 258/ 428	3.8/ 3.8	2.5/ 2.6	2.1/ 2.2	2.4/ 2.5	3/ 1	2/ 1	2/ 1	2/ 1
22	62 748	41	22	15	18	48 804	Uncomminuted biomass (whole tree$_{40}$)	31.980	1 527	5.2	4.3	3.9	4.1	7	4	4	4
23	54 016	38	21	15	17	42 013		31.980	1 314	5.1	4.2	3.9	4.0	6	3	3	3
24	89 053	49	26	18	23	69 264		31.980	2 166	5.6	4.5	4.1	4.3	9	5	5	5
25	64 729	41	22	15	18	47 828	Comminuted biomass (whole tree$_{40}$)	37.683	1 270	3.3	2.4	2.0	2.2	3	2	2	2
26	55 722	38	21	15	17	41 172		37.683	1 093	3.2	2.3	2.0	2.1	3	2	2	2
27	91 865	49	26	18	23	67 878		37.683	1 802	3.7	2.4	2.2	2.4	4	3	2	3
28	78 754	45	24	17	21	22 860/ 12 469	Bio-oil/ bio-char	24.000/ 38.480	953/ 325	3.5/ 3.5	2.4/ 2.5	2.0/ 2.1	2.2/ 2.3	2/ 1	2/ 1	1/ 1	1/ 1
29	103 966	51	27	19	25	30 179/ 16 461		24.000/ 38.480	1 258/ 428	3.8/ 3.8	2.5/ 2.6	2.1/ 2.2	2.4/ 2.5	3/ 1	2/ 1	2/ 1	2/ 1
30	62 748	41	22	15	18	48 804	Uncomminuted biomass (whole tree$_{40}$)	31.980	1 527	5.2	4.3	3.9	4.1	7	4	4	4
31	54 016	38	21	15	17	42 013		31.980	1 314	5.1	4.2	3.9	4.0	6	3	3	3
32	89 053	49	26	18	23	69 264		31.980	2 166	5.6	4.5	4.1	4.3	9	5	5	5
33	64 729	41	22	15	18	61 493	Comminuted biomass (whole tree$_{80}$)	38.480	1 599	3.3	2.4	2.0	2.2	4	3	2	2
34	55 722	38	21	15	17	52 936		38.480	1 376	3.2	2.3	2.0	2.1	3	2	2	2
35	91 865	49	26	18	23	87272		38.480	2 268	3.7	2.6	2.2	2.4	5	4	3	4
36	78 754	45	24	17	21	22 860/ 12 469	Bio-oil/ bio-char	24.000/ 38.480	953/ 325	3.5/ 3.5	2.4/ 2.5	2.0/ 2.1	2.2/ 2.3	2/ 1	2/ 1	1/ 1	1/ 1
37	103 966	51	27	19	25	30 179/ 16 461		24.000/ 38.480	1 258/ 428	3.8/ 3.8	2.5/ 2.6	2.1/ 2.2	2.4/ 2.5	3/ 1	2/ 1	2/ 1	2/ 1

Notes:

1 Weighted Average Transport Distances (WATD) for the respective demand points/biomass procurement areas : Paarl (i), Worcester (ii), Ashton (iii), Rural Cederberge (iv); *Source: Van Niekerk (2011)* .

5.8 Bioenergy generation

This section deals with the conversion of lignocellulosic biomass into electrical energy. As shown in Table 38, below, five different bioenergy conversion system (BCS) configurations are modelled in this study. The first bioenergy conversion system (BCS I) entails an integrated steam-turbine system, where the biomass at max. 20% MC (dry basis) is combusted to generate steam, which is then used in a steam turbine to generate electricity. The same MC is required for BCS II, an integrated gasifier-gas turbine system, where the biomass is upgraded to bio-gas, which in turn, is fed into a gas turbine. BCS III consists of a stationary fast-pyrolysis plant converting biomass (10% MC) into bio-oil and bio-char. The upgraded products are then fed into an integrated boiler-steam turbine system to generate electricity. An integrated steam-turbine system is also assumed for BCS IV, also using bio-oil and bio-char that is produced in a mobile fast-pyrolysis system at the roadside, close to the primary biomass production sites. The last bioenergy conversion system (BCS V) also encompasses mobile fast-pyrolysis systems, but differs in the final conversion step, where only bio-oil is used to generate electricity by directly injecting the liquid into a gas turbine. Also transported to a central facility, the bio-char by-product is assumed to be sold to the fertilising industry, which uses it as an additive for soils.

5.8.1 General considerations and assumptions

For all bioenergy conversion systems (BCSs), an electrical output of $5MW_{el}$ was assumed, based on findings by Roberts (2009), indicating that at an output of $5MW_{el}$, the farm gate price for biomass, is the least sensitive to a biomass producer participation factor. Hence, compared to larger conversion plants, this option shows the lowest risk. The potential gain of larger plants (conversion plants of up to $15MW_{el}$ were considered) could be offset against the higher risk involved, should a lower percentage of farmers choose to participate. Furthermore, electricity is generated on 330 days per year over three shifts of eight hours each, resulting in 7 920 hours of production or 39.6 GWh_{el} per year (refer also to 3.2, the functional unit).

As in a study by Petrie et al. (2004), transmission, distribution, and use of the generated power are not covered. The different LBSs thus provide inventories of undelivered electricity. In addition, only process-related emissions are assessed. The environmental burdens associated with the running and maintenance of offices, workshops, etc. at the respective conversion stations are not incorporated in the assessment. Furthermore, the building and commissioning of conversion plants are not included; neither are the environmental burdens associated with the materials used in construction, and maintenance materials, as was also the case in the study done by Berglund and Börjesson (2006).

Table 38: Bioenergy conversion systems and their related efficiencies

Location		Bioenergy Conversion System (BCS) I	II	III	IV	V
Roadside	Upgrading system	n/a [a]	n/a [a]	n/a [a]	Mobile fast pyrolysis	Mobile fast pyrolysis
Roadside	Upgraded product(s)				Bio-char, bio-gas[b] and bio-oil	Bio-char, bio-gas[b] and bio-oil
Road	Commodity to be transported	Biomass	Biomass	Biomass	Bio-oil and bio-char	Bio-oil and bio-char
Central conversion site	Upgrading system	n/a [a]	n/a [a]	Stationary fast pyrolysis	n/a [a]	n/a [a]
Central conversion site	Upgraded product(s)			Bio-char, bio-gas[b] and bio-oil		
Central conversion site	Feedstock at storage facility	Comminuted biomass	Comminuted biomass	Bio-oil and bio-char	Bio-oil and bio-char	Bio-oil (and bio-char)
Central conversion site	Upgrading unit	Boiler	Gasifier	Boiler	Boiler	-
Central conversion site	Upgraded product	Steam	Fuel gas	Steam	Steam	Bio-oil
Central conversion site	Final conversion	Steam turbine	Gas turbine	Steam turbine	Steam turbine	Gas turbine
Central conversion site	System description	Integrated boiler-steam turbine system	Integrated gasifier-gas turbine system	Integrated boiler-steam turbine system	Integrated boiler-steam turbine system	Direct injection gas turbine
Conversion system		**I**	**II**	**III**	**IV**	**V**
Annual electrical and thermal energy generation	Net electrical energy output	39.6 $GWh_{el.}$/a				
Annual electrical and thermal energy generation	Energy carrier to electricity efficiency (%)	24.1%	22.2%	24.1%	24.1%	26.0%
Annual electrical and thermal energy generation	Required energy input (%)[c]	11.1	1.0	21.1	14.4	3.3
Annual electrical and thermal energy generation	Feedstock upgrading efficiency (%)[d]	Biomass to steam: 87.2	Biomass to bio-gas:	Bio-oil to steam: 89.0% Bio-char to stem: 80.0%		Bio-oil to gas:
Annual electrical and thermal energy generation	Thermal excess energy ratio[c]	3.6	0.66	3.9	3.7	2.5
Annual electrical and thermal energy generation	Thermal energy $GWh_{th.}$/a	142.5 $GWh_{th.}$/a	26.2 $GWh_{th.}$/a	155.4 $GWh_{th.}$/a	146.8 $GWh_{th.}$/a	102.3 $GWh_{th.}$/a
Annual electrical and thermal energy generation	Bio-char (t/a)	n/a [a]	n/a [a]	n/a [a]	n/a [a]	16 461
Biomass input feed requirements	Moisture content[e]	20 wt.%	20 wt.%	10 wt.%	10 wt.%	10 wt.%
Biomass input feed requirements	Biomass at HHV[f]	34 163 t/a	29 409 t/a	48 485 t/a	41 565 t/a	54 871 t/a
Biomass input feed requirements	Biomass at required MC (t/a)[f]	40 995	35 291	53 333	45 721	60 358
Biomass input feed requirements	Energy content at required MC	209.38 GWh/a	180.25 GWh/a	277.45 GWh/a	237.85 GWh/a	314.00 GWh/a [g]
Pyrolysis products	Bio-char (t/a)	n/a[1]	n/a[1]	5 613	12 469	16 461
Pyrolysis products	Bio-oil (t/a)			34 944	22 860	30 179
Pyrolysis con-version [h]	Bio-char (wt.%)			12	30	30
Pyrolysis con-version [h]	Bio-gas (wt.%)[i]			16	15	15
Pyrolysis con-version [h]	Bio-oil (wt.%)			72	55	55

Notes:

[a] Not applicable (n/a).
[b] Bio-gas produced in fast pyrolysis process is used to fuel fast pyrolysis system.
[c] Based on net electrical energy output.
[d] Preserved energy in energy carrier from inherent energy stored in biomass.
[e] Dry basis; biomass pre-dried to required moisture content using exhaust gases from conversion process.
[f] Losses due to pretreatment are not included; values refer only to net biomass requirements.
[g] In case of bioenergy system V, bio-char is sold directly for industrial consumption (e.g. fertilising company); hence, 135.22 GWh stored energy in the bio-char is not utilised.
[h] Biomass-to-pyrolysis-products conversion rate based on dry matter of biomass.
[i] Bio-gas assumed to fuel the pyrolysis systems.

Table 38, above, gives an overview of the five BCS configurations, briefly describing each system in terms of location and type of upgrading and conversion unit, its related intermediate product, as well as its respective upgrading and conversion efficiencies. Furthermore, the net biomass feed requirements, based on the respective efficiencies, and the chemical energy input from the raw material are discussed.

5.8.2 Financial-economic considerations

Various issues and assumptions concerning the financial-economic assessment of the bioenergy systems are discussed below:

- In search of appropriate bioenergy conversion systems, in some cases it was necessary to rely on information from the literature or technology providers based overseas (e.g. USA, Canada, Netherlands or Germany), for which an exchange rate of R11.00 to the Euro and R7.90 to the US dollar was assumed.

- Some of the data used is based on conversion systems working at different production capacities than the above-stipulated $5MW_{el}$. Hence, it was necessary to estimate the cost of the conversion plant where cost data were not available for the particular size or capacity involved. Predictions can be made by using the power relationship known as the *six-tenths factor rule*, if the proposed BCS is similar to one of another capacity for which cost data are available. According to this rule, if the cost of a given unit at one capacity is known, the cost of a similar unit with X times the capacity of the first is $X^{0.6}$ times the cost of the initial unit. The application of the 0.6 rule of thumb for most equipment purchased was, however, an oversimplification, since the actual values of the largest capacity exponent vary from less than 0.3 to greater than 1.0. Because of this, the 0.6 power should be used only in the absence of other information (Peters et al., 2003):

Equation 12: Six-tenth factor rule

$$cost\ of\ equipment\ a = (cost\ equipment\ b)X^{0.6}$$

Source: Peters et al. (2003: 242)

- The economic lifetime expectancy (ELE) for each of the BCSs is assumed to be 20 years (refer also to 3.3.4).

- The renewable energy feed-in tariff (REFIT): In June 2007, the national energy regulator of South Africa (NERSA) commissioned a study of the renewable energy feed-in tariff to support renewable energy, which culminated in the approval of the REFIT guidelines in March 2009.

Based on the levelised cost of electricity, a feed-in tariff of R1.18 per kWh_{el} for bioenergy from solid biomass was announced (NERSA, 2009: 17), with the term of the REFIT power purchase agreement being 20 years, and potential income from the clean development mechanism (CDM) scheme, i.e. so-called carbon credits, being excluded from the REFIT. This means that bioenergy plant operators could separately apply to qualify for the CDM, resulting in additional income.

In March 2011, however, NERSA sought to consult with stakeholders on a review of the tariff levels set in 2009 for renewable energy technologies under the REFIT programme (NERSA, 2011). Until then no REFIT project had commenced due to issues relating to institutional arrangements, although it was assumed that the REFIT programme would commence immediately after the tariff approvals. In approving the 2009 REFIT tariffs, NERSA also undertook that the REFIT tariffs would be reviewed on an annual basis for the first five years of the REFIT programme and every three years thereafter. Due to changes in financial and economic parameters used in the tariff determination of 2009, NERSA revised, *inter alia*, the REFIT tariff for bioenergy from solid biomass, proposing R1.060/kWh_{el} for 2011, R1.084/kWh_{el} for 2012, and R1.108/kWh_{el} for 2013.

The REFIT tariff used in this study is based on the 2011 level, i.e. R1.06/kWh_{el}. However, recent developments have seen another reconsideration of the REFIT tariffs. In August 2011, the South African Department of Energy invited prospective bidders to submit a proposal for the financing, construction, operation and maintenance of renewable energy generation facilities as part of the so-called Renewable Energy Independent Power Producer Procurement Programme (refer to http://www.ipp-renewables.co.za).

- Excess heat or thermal energy can be sold to industrial consumers for heating or, as is more likely in South African conditions, for cooling purposes. Potential buyers of thermal energy are canning factories, fruit wholesalers, etc. In three of the four selected biomass procurement areas, namely, Paarl, Worcester and Ashton, which are located near industrial areas, income is generated not only from selling electricity, but also from selling thermal energy to industrial consumers. Assuming that a potential thermal energy consumer would otherwise have to buy coal (HHV: 30MJ/kg) in order to run a steam boiler to generate thermal energy (80% coal-to-steam conversion efficiency), which is traded at around R1 000 per tonne in the Cape region, a thermal energy tariff of R0.15/kWh_{th} is taken into account. Since thermal energy is a by-product, capital or operational costs are not included.

- In order to promote the participation of the developing world in efforts to reduce greenhouse gasses (GHG), the so-called clean development mechanism (CDM) was developed. After the Kyoto protocol (UN, 1998) came into effect in 2005, it became possible for companies in the developing world (including South Africa) to initiate projects with the aims of reducing GHG emissions, obtaining certified emission reduction (CER) certificates for these projects, and then selling these CERs (also called carbon credits) into the carbon market (Promethium, 2011).

  Using the South African Power-Grid Mix (SAPGM) provided in the GaBi database (PE International, 2006) as a baseline, the avoided net CO_2-equivalent emissions were calculated (in tonnes) to determine the amount of carbon credits per LBS and biomass procurement area. With the functional unit (39.6 $GWh_{el.}$) as a reference, the SAPGM causes fossil fuel-based CO_2-equivalent emissions of 44 951 tonnes per year (refer to Annexure 38). The CO_2-equivalent (fossil) emissions-avoided are specified as the CO_2-equiv. emissions of the reference system less the CO_2-equiv. emissions caused during the life-cycle of the LBSs (refer also to UNCFCCC (2010a, 2010c, 2010b). The latter is a function of the biotic CO_2-equiv. sequestered less emissions from the biotic and fossil CO_2-equiv.

Equation 13: Calculation of CER certificates

$$CER = fossil\ CO_2 em._{reference\ system} - Net\ CO_2 em._{bioenergy\ alternative}.$$

Equation 14: Net CO_2 emissions

$$Net\ CO_2 em. = biotic\ CO_2 sequ. - (biotic\ CO_2 + fossil\ CO_2)$$

Besides selling electrical and thermal energy, carbon credits, assuming a tariff of R100/t of CO_2 emissions avoided, are included in this study and therefore contribute to the income of the LBSs. However, the application of bio-char to soils as a form of carbon capture and storage is currently not included in the CDM methodologies and, thus, is not incorporated in the determination of carbon credits.

The financial-economic information for each bioenergy conversion system is presented in Table 41**,** below. It is subdivided into capital expenditure (CAPEX) and operating expenditure (OPEX). Furthermore, distinctions are made for CAPEX between the biomass upgrading unit (e.g. into bio-oil or bio-char), the conversion unit and the final production step. Similarly, OPEX are subdivided into operation and maintenance (O&M) costs, as well as employment costs (including cost-to-company) for both the upgrading and conversion units.

Table 39: Bioenergy conversion systems and their related capital and operational costs (2011)

			Bioenergy Conversion System (BCS)				
			I	**II**	**III** [g]	**IV** [g]	**V**
CAPEX [a]	Upgrading unit	Base module cost	-	R1 600 000	R82 520 874	R11 848 344	R11 848 344
		No. of units	-	22	1	21	27
		Installation cost	-	-[d]	R66 016 700	-	-
		Total	-	R28 160 000[c]	R148 537 574	R248 815 216	R319 905 278
	Biomass drying system		-	R8 802 227	-	-	-
	Conversion unit	Base module cost	R107 387 165	R1 100 000	R107 387 165	R107 387 165	R43 376 002[i]
		No. of units	1	22	1	1	1
		Installation cost	R30 367 682	R300 000[d]	R 30 367 682	R30 367 682	R34 700 802[h]
		Total	*R137 754 846*	*R25 960 000*[c]	*R137 754 846*	*R137 754 846*	*R78 076 804*
CAPEX – total			R137 754 846	R62 922 227[3]	R286 292 420	R386 570 062	R397 982 082
OPEX	O&M – upgrading unit		- [k]	- [k]	R4 126 044[e]	R4 976 305[f]	R6 398 106[f]
	Employment – upgrading unit		- [k]	- [k]	R2 040 000	R4 140 000	R4 980 000
	O&M – conversion unit		R4 951 584	R1 293 203	R4 951 584	R4 951 584	R867 520[j]
	Employment – conversion unit		R1 430 000	R2 030 000	R1 430 000	R1 430 000	R1 810 000
OPEX – total			R6 381 584	R3 323 203	R12 547 628	R15 497 889	14 055 626

Notes:

[a] Capital investment costs (CAPEX) in South African rands (ZAR).
[b] Annual operating costs (OPEX) in South African rands (ZAR).
[c] Due to the scale of economics, a rebate of 20% on the gasifier and genset units is assumed.
[d] Combined installation cost for both the upgrading and conversion units.
[e] OPEX of upgrading unit assumed as 5% of CAPEX of upgrading unit.
[f] OPEX of upgrading unit assumed as 2% of CAPEX of upgrading unit.
[g] Conversion unit the same as for BCS I.
[h] 80% of conversion unit cost.
[i] Six-tenth rule applied.
[j] OPEX of conversion unit assumed as 2% of CAPEX of conversion unit.
[k] OPEX of upgrading unit included in OPEX of conversion unit.

5.8.3 Emission related considerations

Efficient and complete combustion is a prerequisite of utilising wood as an environmentally desirable fuel. In addition to a high rate of energy utilisation, the combustion process should therefore ensure the complete destruction of the biomass and avoid the formation of environmentally undesirable compounds. The fuel has an influence on the combustion efficiency. At complete combustion, carbon dioxide and water (H_2O) are formed. An incorrect mixture of fuel, type of heating system, and introduction of air may result in an unsatisfactory utilisation of the fuel and a resultant undesirable environmental effect. Efficient combustion is a function of variables such as high temperature, excess oxygen, combustion time and mixture of fuel.

Besides factors relating to the conversion technology (such as reactor type or filter technology) or to the conversion system (such as reactor temperature or residence time), biomass feedstock properties such as its elemental composition have a great influence on the properties of intermediate products, as well as after its final combustion, on the related exhaust gas emissions. The determination of exhaust gas emissions for the BCSs proved to be challenging, since no actual emission data for each of the BCSs using biomass with the specifications stated in 1.6 is available. Some studies concerned with bioenergy conversion are based on hardwoods such as eucalyptus (Cuña Suárez et al., 2010; Oasmaa et al., 2010; Corujo et al., 2010), but in most cases where conversion emission data is available, biomass such as softwoods (e.g. pine) was used, differing considerably in elemental composition, calorific value and biomass density.

In order to overcome this problem, a simplified approach was used to determine the emissions generated in the process of converting woody biomass-based fuel into energy, applying the so-called thermo-chemical equilibrium and *theoretical* or *stoichiometric* oxygen or air requirement (Perry, 1997: 25). Assuming complete combustion of the feedstock, emissions are based on the amount of oxidant (oxygen or air) that is just sufficient to burn the carbon, hydrogen, and sulphur in a fuel to carbon dioxide, carbon monoxide, water vapour, and sulphur dioxide.

Stoichiometry includes the basic laws of chemistry, such as the law of conservation of mass and the law of definite proportions. In general, chemical reactions combine in definite ratios of chemicals. Since chemical reactions can neither create nor destroy matter, nor transmute one element into another, the amount of each element must be the same throughout the overall reaction. For example, the amount of C on the reactant side must be equal to the amount of C on the product side. In other words, only that much carbon can be emitted, as carbon contained in the feedstock is combusted during the conversion process.

Gas stoichiometry is the quantitative relationship (ratio) between reactants and products in a chemical reaction with reactions that produce gases. It applies when the gases produced are assumed to be ideal, and the temperature, pressure, and volume of the gasses are all known.

Hence, the gas ratios applied in this study represent a lower limit of emissions, but give some indication of the emissions to expect. Software packages, such as the NASA chemical equilibrium programme or ASPEN could have been used for more accurate emission estimates, requiring additional information on enthalpy and combustion conditions. However, this would have entailed a study in itself, therefore, going beyond the scope of this study.

Assuming complete combustion of the bioenergy feedstock (biomass, bio-oil, bio-char or bio-gas) and based on various considerations, the following assumptions have been made. Of the carbon in the feedstock, 99.9% is assumed to be emitted as CO_2, with the remainder (0.1%) emitted as carbon monoxide. A greater proportion of CO emissions would represent a significant loss of energy. All hydrogen contained in the feedstock is assumed to be emitted as H_2O. Depending on the combustion conditions, nitrogen forms mostly NO which oxidises into NO_2 upon contact with the air. Hence, it is assumed that all N is released as NO_2. Due to the low content of S in the biomass, technology providers often present the sulphur (S) value as zero. However, over a long period, a significant release of S gasses can be expected. S emissions are not dependent on the combustion conditions and, therefore, do not differ for the various conversion processes. It is assumed that of the S contained in the bioenergy feedstock, 25% (Meincken, 2010) is released as a gas (assuming 100% SO_2). Generally, more than 85% SO_2 is formed, with the difference mostly being SO_3. If SO_2 gas emissions appear to be too high, the gas can be cleaned using scrubbers. The remaining constituents of the bioenergy feedstock are assumed to be completely released to the air in the form of dust/particle matter (PM). Cyclones or flue/exhaust gas filter systems could be fitted for the removal of PM in the exhaust gas.

Some of the bioenergy conversion systems require a considerable amount of water during the electricity generation process. However, it is assumed that in each case a closed water cycle is implemented. Thus, potential water consumption during the conversion process has not been included in the LCA.

Extracting biomass from plantations entails removing important nutrients, which in some cases can increase acidification and decrease productivity, if not compensated for. Recirculating ash, the only 'waste' in lignocellulosic bioenergy systems, could be an option for reducing fertiliser inputs. However, so far, large-scale ash recirculation systems are not commercially available and are therefore not demonstrated (Forsberg, 2000: 23). Thus, if not released to the air as particle matter, woody biomass ash is considered to be used as landfill or as construction material.

5.8.4 Bioenergy conversion system I

The first bioenergy conversion system consists of a biomass-fired integrated steam turbine system, representing the most established commercial option for the production of electricity from wood. The biomass is burned in a boiler to produce hot gasses, producing steam from the hot gasses via a heat exchanger, and then generating power from the steam using a steam turbine.

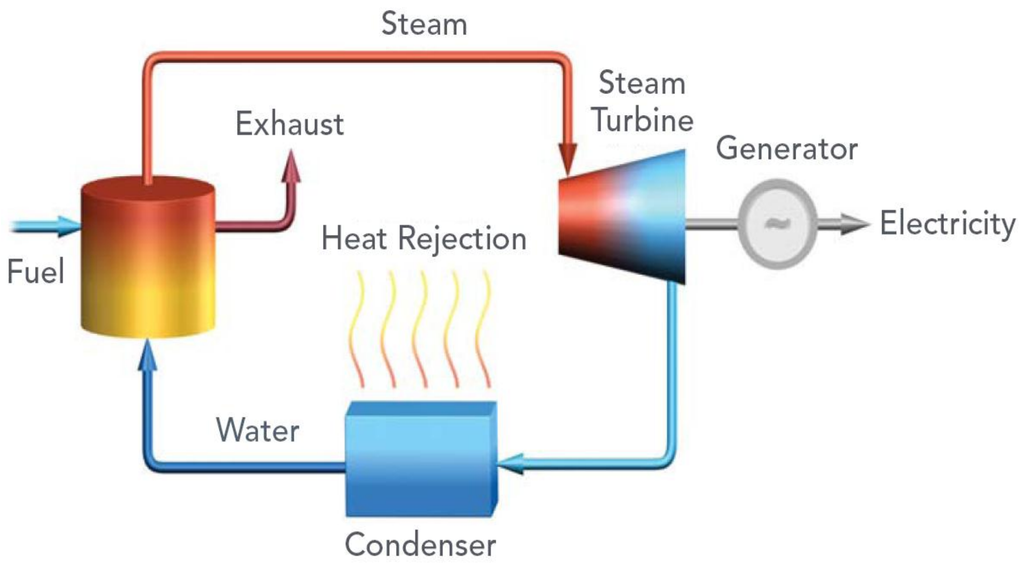

Figure 33: Steam cycle of conventional integrated steam turbine systems

Source: Envergent Technologies (2010)

The assumptions made for BCS I are based on data from previous projects in South Africa (Nukor, 2010), namely, a 5.25 MW_{el} CHP plant combining a John Thompson boiler with a MAN steam-turbine. The turnkey cost, which includes all system components as well as installation costs, amount to R137.8 million, with annual operating costs of almost R6.4 million. The latter encompasses various cost components such as employment costs (cost-to-company) for one plant manager and one engineer, each earning R400 000/year, and R70 000 per year for nine plant operators (three per shift), costs for water conditioning, maintenance costs (1.5% of capital investment costs), and others. Around 10% of the energy produced is required to maintain the energy generated, resulting in an electrical energy production of 5.5MW_{el}. The boiler efficiency (biomass-to-steam efficiency) is 87.2%, i.e. the remainder of the energy inherent in the biomass is lost with the exhaust gases. The exhaust gases, however, are used to dry the biomass to the required moisture content level of 20% (dry basis). The steam-turbine is expected to reach a conversion efficiency of 24.1%. Thus, the net biomass input requirements to ensure continuous energy generation are estimated at 40 995 tonnes per year (20% MC). However, more biomass needs to be produced in order to compensate for potential losses such as occur during harvesting, pretreatment and transport.

As mentioned above, the exhaust gas emissions from the conversion process that are taken into account in the LCA are based on mass balance calculations and the thermo-chemical equilibrium. The approximated emission values used for BCS I are presented in Table 40, below, using the combustion of one tonne of biomass (assuming 20% MC, dry basis) as a reference unit:

Table 40: BCS I flue gas emissions per tonne biomass input

Biomass elemental composition	Wt.%	Dry matter content [a]
C	48.00	400.0
H	5.80	48.3
N	0.25	2.1
S	0.01	0.1
O [e]	42.69	27.1
Ash	3.25	355.8
Total:	100.00	833.3

Exhaust gas emissions [b]				
Element	Gasses formed	%	Stochiometric ratio [c]	Emissions (kg/t) [d]
C	CO_2	99.9	44/12	1 466.52
	CO	0.1	28/12	0.09
H	H_2O	100.0	18/1	870.00
N	NO_2	100.0	46/14	6.85
S	SO_2	25.0	64/32	0.04
Ash	PM [f]	100.0	-	27.1
			Total:	2 370.58

Notes:

[a] Elemental composition of one tonne of biomass less 20% moisture content (dry basis): 1 000kg/1.2=833.33kg
[b] Assuming complete combustion; exhaust gas emission conversion ratios based on Perry (1997)
[c] Mass of gas product (kmol)/ relative atomic mass (kmol), also called relative atomic mass ratio
[d] Exhaust gas emissions in kg per tonne biomass input (20% MC dry basis)
[e] Calculated by difference
[f] Particle matter

5.8.5 Bioenergy conversion system II

For BCS II, the South African-designed and -made System Johansson Gas producer (SJG) by Carbo Consult and Engineering (PTY) LTD was adopted (CCE, 2010). This modular system is based on parallel series of integrated 450Nm^3/h gasifier-gas-turbine systems, each generating an electrical energy output of 255kW$_{el}$. Since the thermal energy is fed back into the system, the thermal excess energy ratio is relatively low at 0.66 of the electrical energy output. Figure 34**,** below, is a schematic illustration of the downdraft wood gasification SJG system. Up to 225kg of biomass (max. 20% MC) are fed into the gasifier, where under vacuum conditions, the biomass is converted into a raw gas, which is passed through a cyclone to remove coarse particles. In a gas scrubber, fine particles are removed and the gas is cooled down to an ambient temperature. Of the energy in the gas, 22% is lost when cooling to an ambient temperature. However, this loss is partially recovered by a heat exchanger. After passing through two more filters, the gas is fed into a generator powering an internal combustion engine.

Due to the design of the reactor, together with a high gasification temperature and a long gas residence time, the gas is tar free. Electrical conversion efficiencies of around 22.2% are reached. The energy input is relatively low at around 1% compared with the electrical energy output, due to the relatively low degree of automation of the system. The net biomass requirements at 20% moisture content are 35 291 tonnes per year, resulting in a net biomass energy input of 18.25GWh.

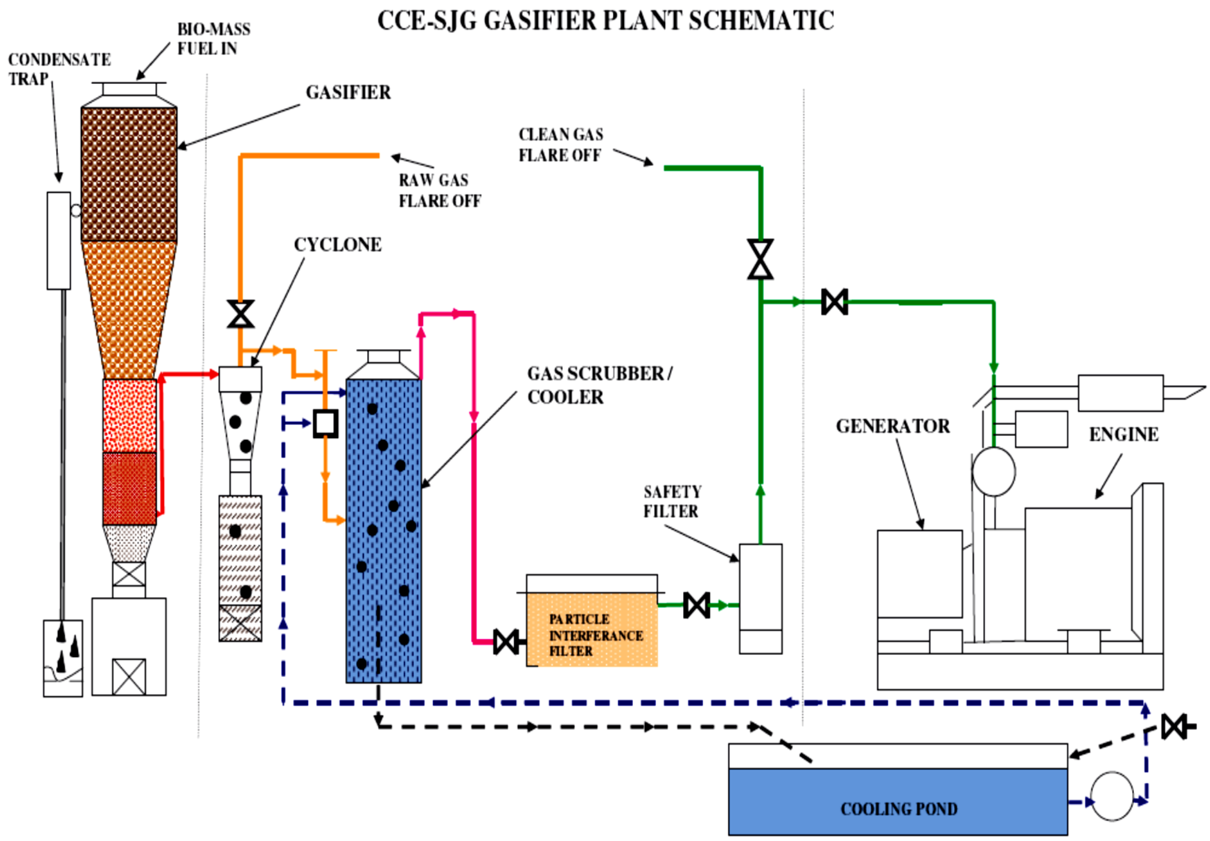

Figure 34: Schematic illustration of System Johansson Gasproducer (SJG)

Source: Eckermann (2009)

Although only 20 units would suffice to ensure the continuous generation of 5MW of electricity, a total of 22 units were assumed in order to accommodate downtime due to maintenance or repairs. The capital investment costs for the gasifier units were quoted in total at R35.2 million (R1.6 million per unit), and for the generating unit and alternator (also called genset), a total of R24.2 million (R1.1 million per unit) was assumed. Including a discount of 20% and installation costs of R300 000 per unit set, as well as the purchase and installation of a drying unit (R8.8 million), the total capital investment costs were estimated at R62.9 million.

The main portion of the operating costs of, in total, R3.32 million per year, arise from employment: seven operators per shift (i.e. 21 operators each at R70 000/a), a plant manager, as well as one engineer (each at R280 000/a) are accounted for. Other operating costs comprise maintenance and repairs of the SJG systems of R853 092, as well as R440 111 for biomass handling, including drying.

In the LCA, the flue gas emissions taken into account for BCS II, similar to BCS I, are based on the thermo-chemical equilibrium. Again, this represents only an approximation. Since the feed-in capacity of each gasifier is limited to 225kg/h (20% MC, dry basis), the emission values presented in Table 41**,** below, are based on hourly feedstock input for each gasifier.

Table 41: BCS II flue gas emissions per gasifier-gas turbine system

Biomass elemental composition	Wt.%	Dry matter content [a]
C	48.00	90.00
H	5.80	10.86
N	0.25	0.47
S	0.01	0.02
O [e]	42.69	80.04
Ash	3.25	6.09
Total	**100.00**	**187.50**

Exhaust gas emissions [b]				
Element	**Gasses formed**	**%**	**Stochiometric ratio [c]**	**Emissions (kg/t) [d]**
C	CO_2	99.9	44/12	329.98
	CO	0.1	28/12	0.02
H	H_2O	100.0	18/1	195.75
N	NO_2	100.0	46/14	1.54
S	SO_2	25.0	64/32	0.01
Ash	PM [f]	100.0	-	6.09
			Total	**533.27**

Notes:

[a] Elemental composition of dry matter of one tonne of biomass less 20% moisture content (dry basis): 225kg/1.2=187.50kg

[b] Assuming complete combustion

[c] Mass of gas product (kmol)/ relative atomic mass (kmol), also called relative atomic mass ratio

[d] Exhaust gas emissions in kg per 225kg biomass input (20% MC dry basis)

[e] Calculated by difference

[f] Particle matter

5.8.6 Bioenergy conversion system III

The third biomass conversion system consists of a stationary fast-pyrolysis system for upgrading the biomass feedstock into the intermediates bio-oil and bio-char, which are then used to fuel an integrated steam-turbine system to generate electricity. As for all BCSs, a total electrical energy output of 39.6GWh_{el} is set as a production target. The steam turbine efficiency is assumed to be the same as for BCS I, namely, 24.1%. The upgrading efficiency of the pyrolysis products into steam is 89% for bio-oil and 80% for bio-char. Together, the pyrolysis system, as well as the integrated steam-turbine system reach a thermal excess energy ratio of 3.9 based on the electrical energy output, resulting in 155.4GWh_{th}. The energy input to sustain both electricity generation, as well as for the fast-pyrolysis process is relatively high at 21.1% of the electrical energy output. In order to maintain the continuous generation of electricity, a net biomass supply of 53 333 tonnes, at a 10% moisture content per year is required, resulting in a net input of biomass energy input of 277.45 GWh.

The data used for the stationary fast-pyrolysis system is based on a rotating cone reactor (RCR) from the Dutch-based Biomass Technology Group (BTG) BioLiquids B.V. (BTG-BTL, 2010).

Biomass particles at an ambient temperature and hot sand particles are introduced near the bottom of the cone, where the solids are mixed and transported upwards by the rotating action of the cone (see Figure 35, above). The organic material is rapidly heated to 450-600°C in the absence of air. Under these conditions, organic vapours, permanent gases and bio-char are produced. The vapours are condensed into bio-oil, resulting in a bio-oil output of 72% (dry basis). Almost 12% of the biomass is converted into bio-char, and the remainder is converted into bio-gas, which is used in the pyrolysis process (Venderbosch and Prins, 2010: 191). The fast-pyrolysis system annually yields 34 944 tonnes of bio-oil and 5 613 tonnes of bio-char.

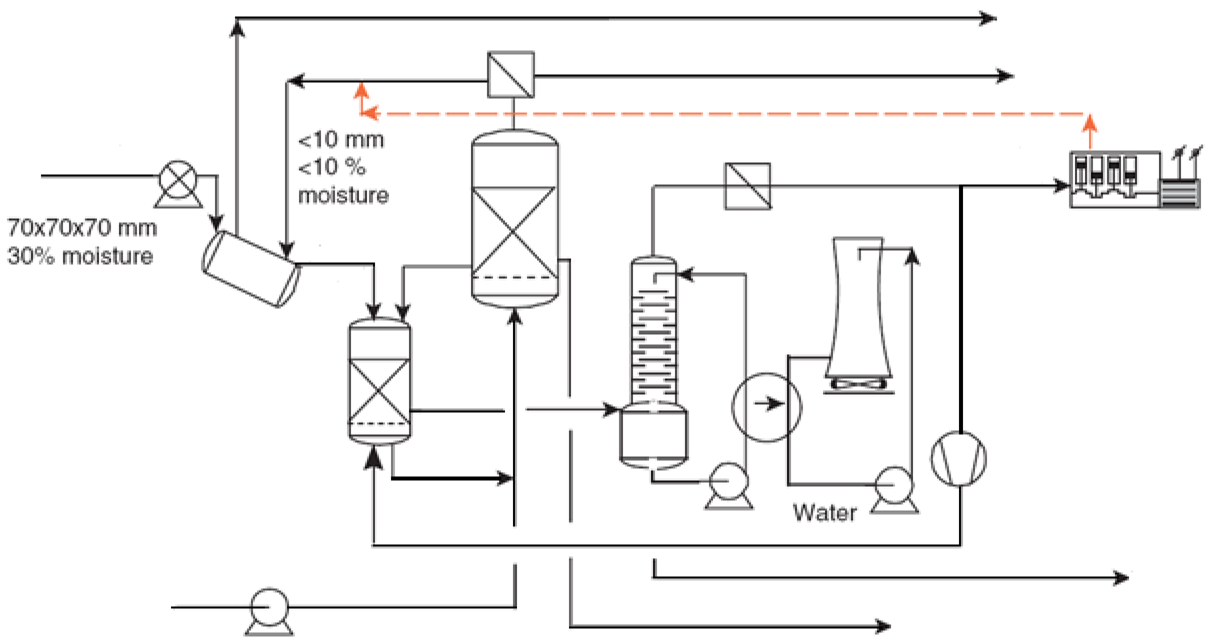

Figure 35: Schematic illustration of stationary BTG-BTL pyrolysis system

Source: Venderbosch and Prins (2010: 191)

For the integrated steam-turbine system, the same assumptions are made as for BCS I, the difference being only in terms of the feedstock-to-steam efficiency, i.e. the boiler efficiency based on the inherent energy content of the feedstock is assumed to be 89% and 80% for bio-oil and bio-char respectively.

The turnkey cost for the biomass upgrading unit, i.e. the pyrolysis system, is quoted at R148.5 million, which includes a capital cost of R82.5 million and R66.0 million for its installation. The operating costs of the pyrolysis system total R6.17 million per year, including costs for operation and maintenance (O&M) of R4.13 million (assumed to be 5% of CAPEX, excluding the installation cost) and a labour cost (cost-to-company) of R2.04 million. The latter can be subdivided into operator costs of R840 000 (4 operators per shift, 3 shifts per day) and R 1.2 million for management and engineering (one manager and two engineers, each earning R400 000 per year). For the conversion unit, the same assumptions as for BCS I were made, i.e. a capital cost including installation of R137.8 million and an operating cost of R6.38 million per year (including O&M and employment). In total, the capital costs amount to R286.3 million, with operating costs of R12.55 million per year.

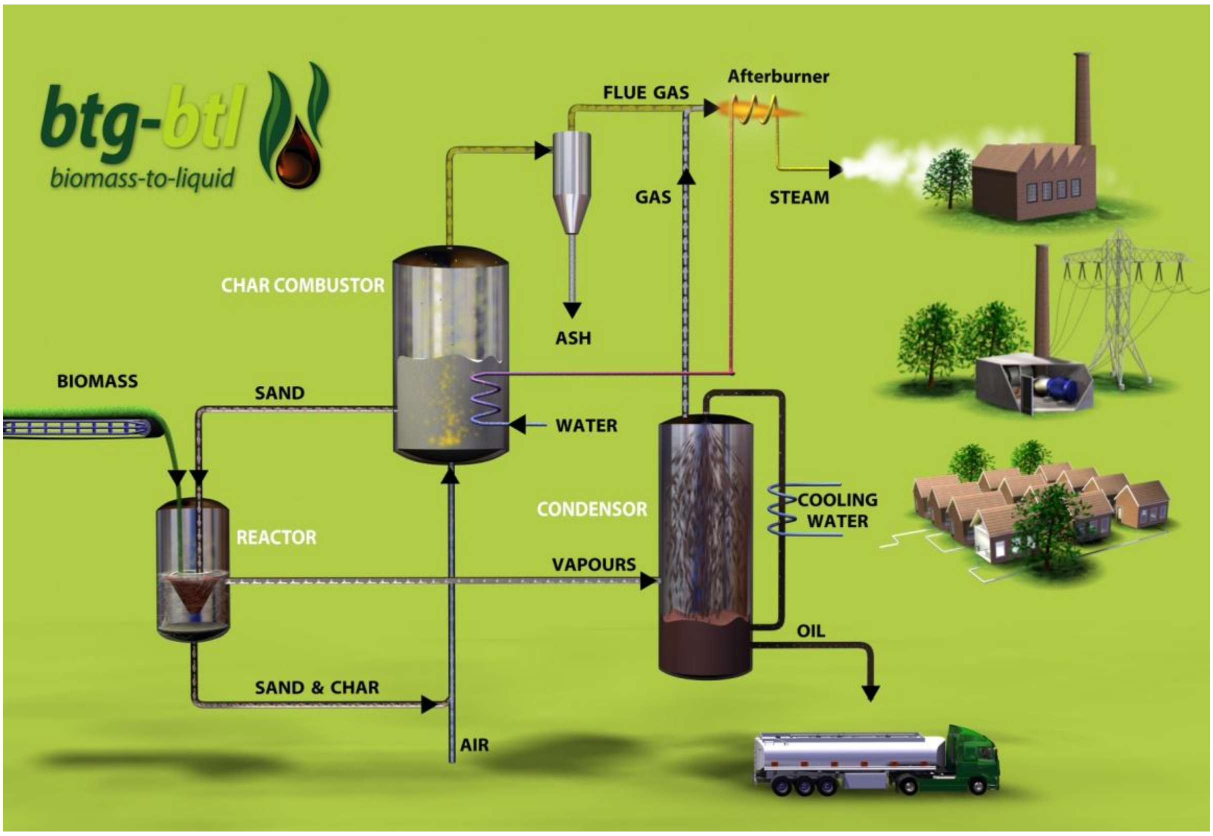

Figure 36: Simplified flowchart of BTG-BTL's fast-pyrolysis system

For the LCA and the related emissions, a number of assumptions had to be made. As mentioned above, the feedstock properties and the conversion system have a great influence on the proportions of the upgraded products (i.e. bio-char, bio-gas and bio-oil), their respective chemical compositions and their respective exhaust gas distributions on combustion.

After reviewing the related literature – refer, *inter alia*, to Sevilla et al. (2011); Kumar et al. (2010); Kumar and Gupta, (1992); Kumar et al. (2011); Bridgwater (2011); Amutio et al. (2011); Venderbosch and Prins (2010); Cuña Suárez et al. (2010); Oasmaa et al. (2010); Corujo et al. (2010); Vassilev et al. (2009); Khodier et al. (2009); NREL (2006); and Turn et al. (2005) – the typical elemental composition of the wood-derived pyrolysis products bio-oil and bio-char is summarised in Table 42, below. In general, the elemental composition of bio-oil is similar to the original feedstock. Around 75wt.% of the bio-char consists of carbon, with a much lower oxygen proportion of around 10wt.%. The mass balance for ash can differ considerably, depending on various parameters of the pyrolysis process. However, for this study, it was assumed that all of the ash (mineral elements, except N and S) contained in the feedstock remains in the bio-char, and that the mass of the bio-char product includes the mass of the stable carbon, ash and volatile matter (refer also to Roberts et al., 2010: 829).

Table 42: Typical elemental distribution of bio-oil and bio-char

Elemental components	**Distribution of wood derived pyrolysis products (wt.%)**	
	Bio-oil	**Bio-char**
Carbon (C)	45.00-60.00	60.00-90.00
Hydrogen (H)	5.20-7.20	0.50-3.00
Nitrogen (N)	0.07-0.79	0.50-1.00
Oxygen[a] (O)	30.00-45.00	8.00-12.00
Sulphur (S)	0.00-0.10	0.00-0.10
Ash[b]	0.00-0.10	0.00-30.00

Notes:
[a] Calculated by difference
[b] Most of the ash is contained in the bio-char, with negligible amounts in the bio-oil and bio-gas

Table 43: Elemental distribution of pyrolysis products calculated for BTG-BTL system

		Bio-oil	**Bio-char**	**Bio-gas[a]**	***Biomass[b]***
HHV		18.77MJ/kg	29.57MJ/kg	6.08MJ/Nm^3 [c]	*19.00MJ/kg*
Mass balance (dry matter)		72.07 wt.%	11.58 wt.%	16.35 wt.%	-
Elemental component distribution (wt.%)	Carbon (C)	49.80	63.33	29.21	*48.00*
	Hydrogen (H)	6.00	1.76	7.78	*5.80*
	Nitrogen (N)	0.10	0.64	0.64	*0.25*
	Oxygen (O) [d]	44.10	6.11	62.37	*42.69*
	Sulphur (S)	0.00	0.09	0.00	*0.01*
	Ash[2]	0.00	28.08	0.00	*3.25*

Notes:
[a] Calculated as difference assuming law of conservation of mass
[b] Elemental composition of biomass feedstock as reference
[c] 1kg biomass feed results in around 2Nm3 gas containing approximately 5.9-6.25MJ/kg chemical energy
[d] Calculated by difference

As described above, the mass balance (wt.%, dry basis) for the BTG-BTL system results in 72wt.% of the biomass feedstock being converted into bio-oil and nearly 12wt.% into bio-char. Based on the law of the conservation of mass, the bio-gas produced in the pyrolysis process was specified as the the original feedstock less the bio-oil and the bio-char.

The elemental compositions listed in Table 43, above, were selected arbitrarily, since no data for the BTG-BTL system using hardwood feedstock with the properties listed in the last column of Table 43 was available. However, the values selected are somewhat representative of each pyrolysis product, while maintaining a constant mass balance.

Table 44: BCS III flue gas emissions of each of the pyrolysis products

Biomass elemental composition	**Wt.%**	**Dry matter content [a]**
C	48.00	436.36
H	5.80	52.73
N	0.25	2.27
S	0.01	0.09
O [e]	42.69	388.09
Ash	3.25	29.55
Total:	**100.00**	**909.09**

Exhaust gas emissions [b]						
Ultimate analysis	**Gasses formed**	**%**	**St. ratio [c]**	**Bio-char**	**Bio-gas**	**Bio-oil**
				kg/t biomass input (10% MC)		
C	CO_2	99.9	44/12	244.15	159.06	1 195.20
	CO	0.1	28/12	0.16	0.10	0.76
H	H_2O	100.0	18/2	16.67	104.07	353.80
N	NO_2	100.0	46/14	2.21	3.10	2.15
S	SO_2	25.0	64/32	0.05	0.00	0.00
Ash	PM [f]	100.0	-	29.55	0.00	0.00
			Total:	**292.78**	**266.33**	**1 551.92**

Notes:

[a] Elemental composition of one tonne of dry biomass less 10% moisture content (dry basis): 1000kg/1.1=909.09kg
[b] Assuming complete combustion
[c] Stoichiometric (St.) ratio: Mass of gas product (kmol)/ relative atomic mass (kmol); also called relative atomic mass ratio
[d] Exhaust gas emissions in terms of kg per tonne biomass input (10% MC dry basis)
[e] Calculated by difference
[f] Particle matter

Similar to the combustion of biomass, the exhaust gas emissions from combusting each of the pyrolysis products are based on the emission assumptions made above. The last three columns of Table 44 show the calculated emissions for combusting each of the pyrolysis products based on inputting one tonne of biomass at 10% moisture content.

5.8.7 Bioenergy conversion system IV

Mobile/portable fast-pyrolysis at the roadside is proposed for BCS IV. After having been transported to and stored at the central conversion site, the pyrolysis products bio-oil and bio-char are further used in an integrated steam turbine system to generate electricity.

The assumptions made for the mobile fast-pyrolysis system are based on the MPS100 system from the Canadian based Agri-Therm Inc. company. The collapsible pyrolysis unit is fitted to a heavy-duty, standard-sized towing tractor for easy transportation and setting up. The fluidised bed reactor is fitted with a patented heat recovery system, allowing the pyrolysis process to operate at higher temperatures and lower input energy requirements. The MPS100 can support variable feedstock sizes – up to 2.5cm in diameter and 10cm in length. The feeding capacity per unit is up to 416kg per hour at a 10% moisture content (dry basis) with an output of 208kg of bio-oil (55wt.% based on biomass dry matter input) and 113kg bio-char (30wt.%). The bio-gas produced in the pyrolysis process is used to fuel itself.

Similar to those for BCS I, the assumptions made for the conversion unit are based on a system combining a John Thompson boiler and a MAN steam turbine. The same boiler efficiencies for the combustion of bio-oil and bio-char as for BCS III are assumed, i.e. 89% and 80% respectively. The steam turbine reaches conversion efficiencies of up to 24.1%.

Besides a net annual electrical output of 39.6 GWh_{el}, excess thermal energy of 146.8GWh_{th} is also produced, assuming a thermal excess energy ratio of 3.7. The energy input for the conversion unit based on the electrical energy output is 14.4%. To maintain the continuous generation of electricity, at least 45 721 tonnes (10% MC) of biomass are required annually, which translates into 237.85 GWh of chemical energy inherent in the biomass.

Unlike the stationary upgrading units, which are assumed to have an uptime of 24 hours on 330 days per year, the mobile fast-pyrolysis units only produce for 16 hours or two shifts a day, which results in a total of 21 upgrading units being required in order to ensure continuous electricity generation (14 units would be required if 24 hourly production was assumed). The upgrading unit's capital costs, including the transportation unit are R11.9 million ($1.5million), or a total of R248.8 million for all 21 upgrading systems. Any discount due to the scale of economics was not suggested by the provider. As for BCS I and III, the basic module costs for the conversion unit are estimated at R107.4 million, to which R30.4 million for installation needs to be added. The total capital investment costs are therefore R386.6 million.

One skilled operator is required to run a mobile fast-pyrolysis unit, resulting in a total of 42 upgrading unit operators. The conversion unit requires three operators per shift, one engineer for technical support, as well as one general manager supervising the whole operation. Thus, total employment costs including cost-to-company costs add up to R5.57 million per year. Operation and maintenance costs of the upgrading unit are assumed to be 2% of the unit's capital cost, i.e. R236 967/unit (R4.98 million in total). Including the O&M costs for the conversion unit of almost R5.0 million, the total operating costs for BCS IV are R15.5 million per year.

Figure 37: Agri-Therm's MPS100 mobile fast-pyrolysis unit

Following the same approach as for BCS III, the flue/exhaust emissions of the respective pyrolysis products are specified by assuming complete combustion and are based on the law of the conservation of mass. The elemental composition of bio-oil and bio-char, which are presented in Table 45, below, were chosen arbitrarily, but are within the boundaries of typical product properties and maintain mass balance. The elemental composition of biogas is calculated as the difference between the elemental composition of the biomass feedstock less the bio-oil and the bio-char.

Table 45: Calculated elemental distribution of pyrolysis products based on Agri-Therm system

		Bio-oil	Bio-char	Bio-gas [a]	*Biomass* [b]
HHV		18.77MJ/kg	29.57MJ/kg	6.08MJ/Nm^3 [c]	*19.00MJ/kg*
Mass balance (dry matter)		55.00 wt.%	30.00 wt.%	15.00 wt.%	-
Elemental component distribution (wt.%)	Carbon (C)	43.21	73.97	13.62	*48.00*
	Hydrogen (H)	7.73	3.22	3.88	*5.80*
	Nitrogen (N)	0.14	0.46	0.23	*0.25*
	Oxygen (O) [d]	48.92	11.51	82.24	*42.69*
	Sulphur (S)	0.01	0.11	0.03	*0.01*
	Ash[2]	0.00	10.84	0.00	*3.25*

Notes:

[a] Calculated as the difference assuming the law of conservation of mass

[b] Elemental composition of biomass feedstock as reference

[c] 1Kg biomass feed results in around 2Nm^3 gas containing around 5.9-6.25MJ/kg chemical energy

[d] Calculated by difference

Flue gas emissions from bio-gas arise during the pyrolysis process, where they are used to fuel the upgrading unit. The bio-oil and bio-char are combusted in the respective boiler systems at the conversion unit. The emissions to air for each pyrolysis product taken into account in the LCA are presented in Table 46, below.

Table 46: BCS IV flue gas emissions of each of the pyrolysis products

Biomass elemental composition	Wt.%	Dry matter content [a]	Exhaust gas emissions [b]						
			Ultimate analysis	Gasses formed	%	St. ratio [c]	Bio-char	Bio-gas	Bio-oil
							kg/t biomass input (10% MC)		
C	48.00	436.36	C	CO_2	99.9	44/12	738.96	68.05	791.39
H	5.80	52.73		CO	0.1	28/12	0.47	0.04	0.50
N	0.25	2.27	H	H_2O	100.0	18/2	79.04	47.66	347.85
S	0.01	0.09	N	NO_2	100.0	46/14	4.12	1.05	2.30
O [e]	42.69	388.09	S	SO_2	25.0	64/32	0.01	0.2	0.01
Ash	3.25	29.55	Ash	PM [f]	100.0	-	29.55	0.00	0.00
Total	**100.00**	**909.09**	**Total**				**852.15**	**116.82**	**1 142.06**

Notes:

[a] Elemental composition of dry matter of one tonne of biomass less 10% moisture content (dry basis): 1000kg/1.1=909.09kg

[b] Assuming complete combustion

[c] Stoichiometric (St.) ratio: Mass of gas product (kmol)/relative atomic mass (kmol), also called relative atomic mass ratio

[d] Exhaust gas emissions in kg per tonne biomass input (20% MC dry basis)

[e] Calculated by difference

[f] Particle matter (PM)

5.8.8 Bioenergy conversion system V

Like BCS IV, the fifth biomass conversion system encompasses a mobile pyrolysis system as an upgrading unit. For the conversion, however, a different technology is assumed. After transportation of both pyrolysis products bio-oil and bio-char to a central conversion site, only the bio-oil is used to generate electricity, i.e. in a direct-injection gas turbine at a central conversion site. The bio-char is not used to generate electricity. Instead, it is assumed to be sold to agro-chemical companies as a fertiliser additive.

For the upgrading unit, the same assumptions as for BCS IV are made, i.e. up to 416kg of biomass at a moisture content of 10% can be fed into the system, yielding 208kg of bio-oil and 113kg of bio-char (55wt.% and 30wt.% respectively based on dry biomass, i.e. dry basis). The conversion unit is based on a Tarsus 60 X1 combined-cycle gas turbine plant – refer to the *Gas Turbine World Handbook* (2010) and Farmer and De Biasi (2010). Due to its high oxygen content and the presence of a significant proportion of water, the heating value of bio-oil is much lower than for fossil fuel (Venderbosch and Prins, 2010: 197). These and other differences in fuel properties result in relatively low conversion efficiencies for bio-oil in gas turbines. For this study, a conservative 26.0% was assumed, similar to values found in Lupandin et al. (2005), resulting in a net biomass requirement of 60 358 tonnes per year at 10% moisture content. Around 3.3% energy input on an electrical energy output basis is required for the system. Besides the electrical energy output of $5MW_{el}$, a thermal excess energy of $12.5MW_{th}$ is generated (thermal excess energy ratio of 2.5). Another by-product is the marketable bio-char, which amounts to 16 461 tonnes per year.

The conversion unit generates electricity for 24 hours on 330 days per year, whereas the upgrading units produce bio-oil and bio-char only during two shifts, each of eight hours a day. Only bio-oil is used for generating electricity. Both, the time and product constraints, result in 27 mobile fast-pyrolysis units being required, ensuring continuous production of the conversion unit. Therefore, the total capital costs for the upgrading units are calculated at R319.91 million.

In order to conform to the proposed 5MW electrical energy output requirements, the six-tenth factor rule had to be applied for the conversion unit. Since the Tarsus 60 X1 has a proposed electrical energy output of 7.3 MW and a capital cost of R54.44 million ($6.89 million), the base module costs for the gas turbine are calculated as R43.38 million, and together with installation costs of R34.70 million (80% of the base module cost), the total capital expenditure for the conversion unit is R78.08 million.

Similar to BCS IV, one skilled operator is required to run a mobile fast-pyrolysis unit, resulting in 54 skilled operators being required for the upgrading units. They are supervised by two upgrading unit managers, as well as three engineers. One plant manager, one engineer and three operators are assumed to be required for the conversion unit. The total annual employment costs are calculated as R6.79 million. Expenditure for O&M for both the upgrading units as well as for the conversion units is assumed to be 2% of the base unit costs, i.e. R6.40 million for the mobile fast-pyrolysis systems and R0.87 million for the gas turbine, resulting in a total operating expenditure of R14.06 million per year.

For the LCA, the flue gas emissions of the mobile fast-pyrolysis units are as assumed for BCS IV (refer to column 9 in Table 45, above). Similarly, the emissions to air from the compressed combustion of bio-oil in a gas turbine are also per the combustion of bio-oil for BCS IV (refer to column ten in Table 45**,** above). However, the flue gas emissions per produced energy unit are less for BCS V than for BCS IV, due to the greater conversion efficiency.

As mentioned above, the transmission, distribution, and use of the generated power are not covered. Similarly, the transport to and usage of bio-char by industrial consumers is not included in the assessment. Nevertheless, the bio-char is assumed to be sold to fertiliser companies for addition to soils. The stability of bio-char does vary with feedstock, processing, and environmental conditions. For this assessment, high yields of stable carbon are assumed. With this in mind, a conservative estimate of 80% of the C in the char as being stable is assumed (Lehmann et al., 2009; Baldock and Smernik, 2002). The remaining 20% of the C is labile and is released into the atmosphere as biogenic CO_2 within the first few years of applying it to the soil (Roberts et al., 2010).

5.9 Conclusions

In the goal and scope definition (the first phase of a life-cycle assessment), as described in Chapter 4, a set of 37 lignocellulosic bioenergy systems using lignocellulosic biomass grown in short-rotation coppice systems as a feedstock was defined. This included a definition of the functional unit and system boundaries. Within the Cape Winelands District Municipality, which forms the geographical boundaries, four biomass procurement areas, differing in biomass productivity and availability of biomass production sites, were selected.

The second phase of a life-cycle assessment is defined as a life-cycle inventory analysis (LCI), as described in Chapter 5 involves data collection and calculation procedures to quantify the relevant inputs and outputs of a product system (ISO 14040, 1997). Thus, based on the LCA framework, each process/activity illustrated in Figure 11 leading to the set of 37 lignocellulosic bioenergy systems for the Cape Winelands District Municipality was specified, not only in terms of environmental input and output flows, as defined in the ISO standards 14040-14044, but also in terms of financial-economic and socio-economic performance. The financial-economic data comprises capital and operating expenditure for each unit-process, as well as expected revenues from selling electricity, the main product, and from selling by-products such as thermal energy for cooling or heating, or bio-char to the fertilising industry. Furthermore, for each system, the amount and type of the direct employment creation potential, a socio-economic indicator, were determined.

Since each LBS consists of at least five production phases, namely, primary biomass production; harvesting and forwarding; biomass pretreatment including comminution, drying and fast-pyrolysis; secondary transport; and biomass upgrading and electricity generation, a myriad of information and data across the four biomass procurement areas has been collected and processed. The following chapter encompasses the life-cycle impact assessment (LCIA), the third phase of an LCA, which is – from conventional LCA perspective– aimed at assessing the results of the life-cycle inventory to better understand their environmental significance by translating the environmental loads of each LBS into environmental impacts, such as global warming potential or eutrophication potential.

Furthermore, the relevant data for the financial-economic assessment is translated by means of multi-period budgeting into key parameters, such as internal rate of return or risk of investment in terms of cost, describing the financial performance of each LBS per biomass procurement area. Similarly, the socio-economically relevant data describing the potential of creating direct employment is translated into three income categories, also to allow a comparison of the LBSs.

6 CHAPTER: LIFE-CYCLE IMPACT ASSESSMENT

6.1 Introduction

The previous chapter covers the life-cycle inventory, based on the LCA framework. This involves data collection and calculation procedures to quantify the relevant inputs and outputs occurring during the production phases for each of the lignocellulosic bioenergy systems (LBSs) considered. This chapter deals with the life-cycle impact assessment (LCIA), which is the third phase of the life-cycle assessment as described in the international standard (ISO 14040, 1997). The purpose of the LCIA is to assess a product system's life-cycle inventory results, to better understand their environmental significance (ISO 14042, 2000). The impact assessment is achieved by translating the environmental loads from the inventory results into environmental impacts, such as acidification, ozone depletion, and global warming potential (Baumann and Tillman, 2004: 129).

There are several reasons for translating environmental loads into impacts, such as to make the results more environmentally relevant, comprehensible and easier to communicate, as well as to improve the readability of the LCI results. The number of result parameters for the latter can range from 50 to 200 or even more (Baumann and Tillman, 2004: 129). Through the LCIA, the number of parameters can be reduced by grouping the environmental loads of the inventory results into environmental impact categories. The LCIA is also useful for making results more comparable, which is particularly relevant when comparing a set of alternatives, as is the case in this study.

Other important considerations in terms of environmental impacts are, for instance, the effects of introducing bioenergy systems on biodiversity, as well as on water balance. The *biodiversity intactness index* or the *water footprint* are assessment methods which have the potential to determine such environmental impacts, but since they are not included in the commonly accepted LCIA methods, only a general discussion is given below. In addition, both environmental impacts have been dealt with *a priori* in a land suitability assessment by means of geographic information systems (GIS).

Furthermore, using the LCA framework as a guideline, a set of financial-economic and socio-economic criteria are defined, against which the LBSs are assessed. By means of multi-period budgeting (MPB), financial-economic data is translated into key parameters describing the performance of each LBS, making them more comparable. The financial-economic criteria are used to describe the LBSs' profitability and cost structures, the former being an indicator of overall performance, and the latter being an important consideration in terms of risk of investment. This allows for a comparison of LBSs, as well as for a comparison of each LBS in terms of biomass procurement area.

The socio-economic impact of the LBSs in terms of employment creation potential are subdivided into three income categories, based on the productivity data of each production phase used in the MPB models. Similar to the environmental impacts biodiversity and water balance, food security, another socio-economic impact, is briefly discussed.

6.2 Environmental criteria

This section deals with not only the impact assessment categories commonly found in life-cycle impact assessments such as abiotic depletion potential and global warming potential, among others, but it also presents a brief discussion on biodiversity and water balance.

6.2.1 LCA impact categories

The LCA software package GaBi 4.4 offers a variety of life-cycle impact assessment (LCIA) methods, such as the so-called CML 2001, Eco-Indicator 95, EDIP 2003, Impact 2002+ and TRACI. Commonly used is the frequently updated CML 2001 method, which is also applied in this study.

CML 2001 is a collection of impact assessment methods that restricts quantitative modelling to the relatively early stages in the cause-effect chain, to limit uncertainties and group LCI results in mid-point categories, according to themes. These themes are common effects (e.g. climate change) or commonly accepted groupings of these (e.g. ecotoxicity) (PE International, 2010). The version of the CML 2001 normalisation factors used for this study is from November 2009.

The data for the impact categories CML 2001 are from the Centre of Environmental Science (‘Centrum Milieukunde Leiden’ or CML) at the University of Leiden, The Netherlands, published in the ‘Handbook on Life Cycle Assessment’ (Guinée et al., 2002b). Furthermore, a spreadsheet presents characterisation factors for more than 1 700 different flows (PE International, 2011).

The CML 2001 normalisation data is based mainly on conditions for the Netherlands and Western Europe according to the information of the CML. Data for other countries and geographical units are from computations and information supplied by PE International GmbH (PE International, 2006). The normalisation data mostly being based on European conditions may be reason for criticism, but due to the lack of localised data, it was the only available source.

A summary of the results for each impact category discussed in this section can be found in Annexures 38-44, subdivided into LBSs and biomass procurement areas. The complete and detailed results for each LBS and biomass procurement area, including all CML 2001-Nov. 2009 impact categories are also detailed in the Annexures (see Annexures 1-37).

6.2.1.1 Abiotic depletion potential

How impact assessments of resource depletion should be done, is one of the most debated topics (Baumann and Tillman, 2004: 145). In general, resources can be divided into renewable and non-renewable resources or into abiotic and biotic resources. Abiotic resources are natural resources (including energy resources) such as iron ore, crude oil and wind energy, which are regarded as non-living; biotic resources are ‘living’, i.e. those with a biological character.

Three types of abiotic resources can be distinguished: deposits, funds and flows. Deposits, which are sometimes also called non-renewable resources, are resources that are not regenerated within human lifetimes, e.g. fossil fuels, minerals and clays. Funds are resources that can be regenerated within human lifetimes, e.g. ground water and top soil. Flows are resources that are constantly being regenerated, e.g. rivers, wind and solar energy. Another term for flows is renewable resources (Baumann and Tillman, 2004: 146).

The CML 2001 impact assessment method collection encompasses two types of abiotic depletion potentials (ADPs), namely, ADP elements (measured in kg stibnite or Sb-equivalent) and ADP fossil (measured in MJ), where the stock of the resource itself is considered a key problem. The characterisation model is a function of the natural reserves of the resources, combined with their rates of extraction. The method is made operational for many elements and fossil fuels (more specifically, the energy content of fossil fuels). The natural reserves of these resources are based on ‘ultimate reserves’, that is on concentrations of the elements and fossil carbon in the earth’s crust (Van Oers et al., 2002: 12).

The characterisation factor is the abiotic depletion potential (ADP). This factor is specified for the extraction of elements ($ADP_{elements}$), a relative measure, with the depletion of the element ‘antimony’ as a reference, and the consumption of fossil fuels (ADP_{fossil}) measured in energy units (e.g. Gigajoule) respectively (Van Oers et al., 2002: 12). Only ADP_{fossil} (GJ) is taken into consideration in this study, since it deals with the generation of energy and not with the extraction and use of elements. The results generated for the $ADP_{elements}$ of the LBSs support this, with the abiotic resource consumption of the elements by the LBSs being one to a maximum of four kg per year (refer to Annexures 1-37).

Figure 38, below, illustrates the performance of the LBSs regarding their respective ADP_{fossil} (GJ) and the respective biomass procurement area, i.e. Paarl (blue bars), Worcester (orange bars), Ashton (green bars) and the Rural Cederberge (red bars). The worst performing alternative across all locations, having the greatest abiotic depletion potential, is LBS 16, which can be explained by the relatively low overall conversion efficiency of BCS 3 (centralised fast-pyrolysis combined with a steam-turbine conversion system), resulting in greater biomass demand and, thus, requiring more up-stream activities. This is intensified by the low biomass output efficiency during motor-manual harvesting, since only logs are used further on in this process, necessitated by manual loading and unloading.

LBS 34, which falls within BCS II, a gasification bioenergy system, is characterised by a relatively higher overall conversion efficiency, resulting in fewer up-stream activities being required. In addition, harvesting with a combine harvester, where the trees are felled and comminuted in a single operation, results in a lower combined fuel consumption and thus in a lower ADP_{fossil} compared with harvesting systems where harvesting and comminution occur in separate phases. This greater efficiency even compensates for the greater emissions during the secondary transportation of the comminuted biomass, which contains 80% moisture content (dry basis), instead of 40% in the case of the other harvesting systems.

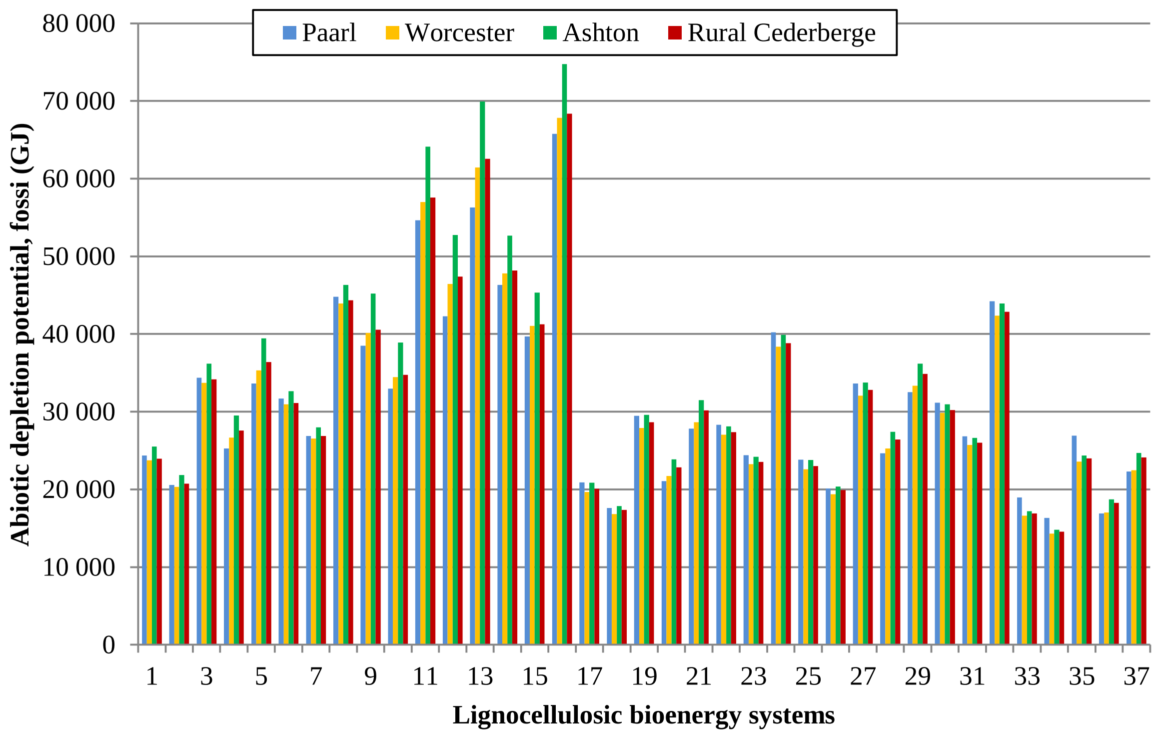

Figure 38: The LBSs' abiotic depletion potential colour coded according to BPAs

For the LBS key, refer to Figure 11

Using the same assumptions made for the functional unit, i.e. an electrical energy output of 39.6 GWh per year, the South African power-grid mix (SAPGM) (PE International, 2006) causes an ADP_{fossil} of 429 458GJ (refer to Annexure 38), compared with an average for the LBSs across all biomass procurement areas of 32 310GJ, which is less than 8% of the SAPG mix. Worcester's LBS 34 accounts for the smallest ADP with 14 311GJ (3.3% of the SAPGM), while Ashton's LBS 16 accounts for the greatest ADP with 74 736GJ (17.4% of the SAPGM).

6.2.1.2 Acidification potential

The major acidifying pollutants are SO_2, NO_x, HCl and NH_3. Acid rain is only one form in which acid deposition occurs. Fog, snow, and dew also trap and deposit atmospheric pollutants. Furthermore, dry acidic particles and aerosols are converted into acids when they dissolve in surface water or contact moist tissues (e.g. in the lungs) (Baumann and Tillman, 2004: 155).

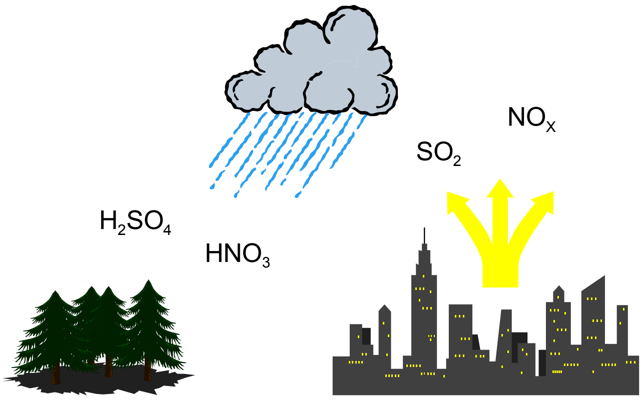

Figure 39 Impact pathways leading to acidification

Source: Heijungs et al. (1992)

The acidification of soil and water occurs predominantly through the transformation of air pollutants into acids. This leads to a decrease in the pH levels of rain water and fog from 5.6 to levels lower than 4. This damages ecosystems, of which forest dieback is the most well-known impact. Acidification has direct and indirect damaging effects (such as nutrients being washed out of soils or an increased solubility of metals in soils). But even buildings and building materials may be damaged. Examples include metals and natural stones, which are corroded or disintegrated at an increased rate (PE International, 2010). However, actual acidification varies depending on where the acidifying pollutants are deposited. The actual impact is governed by, for example, the buffering capacity of soils and waters, climatic conditions, (amount of light and temperature) and the rate of harvesting (Baumann and Tillman, 2004: 155). Thus, although considered a global problem, the regional effects can vary. Various approaches to accounting for local differences have been suggested, but to date, there are few easily applicable methods. Figure 39 displays the primary impact pathways of acidification.

What acidifying pollutants have in common is that they form acidifying H^+ ions. A pollutant's potential for acidification can thus be measured by its capacity to form H^+ ions. This fact has been used in characterisation modelling in LCAs. The acidification potential (AP) is defined as the number of H+ ions produced per kg of substance relative to SO_2 ($AP_{substance} = n_{H+substance}/n_{H+SO_2}$) (Heijungs et al., 1992). The acidification potential thus reflects the maximum acidification a substance can cause.

When analysing the AP results, graphically illustrated in Figure 40, it becomes quite apparent that the main drivers for AP are the respective BCSs with their overall conversion efficiencies. At least 85% of the AP originates from the BCSs (refer to Annexures 1-37).

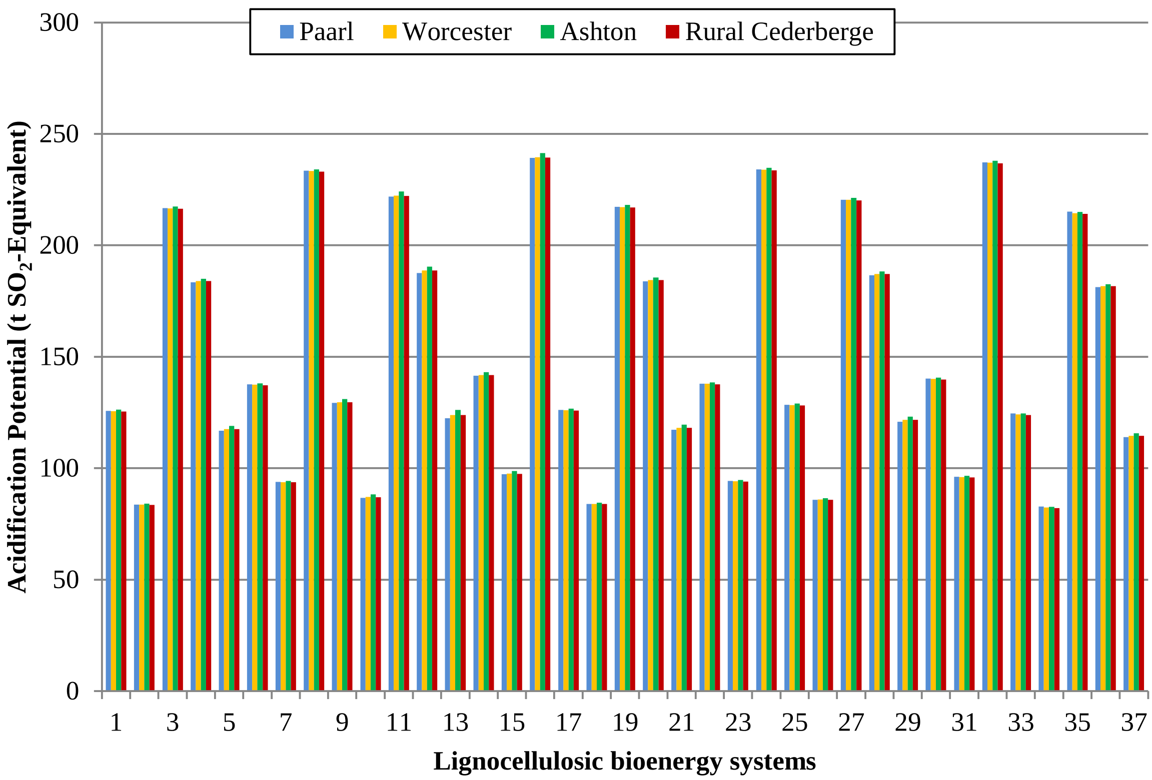

Figure 40: The LBSs' acidification potentials colour coded according to BPAs

For LBS key, refer to Figure 11

Based on the same functional unit, the South African power grid mix (SAPGM) shows an acidification potential of 531 tonnes per year (refer to Annexure 38), at least 2.2 times that of the proposed LBSs. The best case-scenario shows (BPA II' and BPA IV's LBS 34) a comparatively impressive ratio of 6.5.

All LBSs using BCS II, the gasifier-gas-turbine system, show the lowest AP, with 83 to 96 tonnes per year (tpa). The LBSs using BCS V have the second-lowest acidification potential, varying from 114 to 123tpa. The LBSs using BCS I cause an AP of 124 to 143tpa, followed by those using BCS IV, with 181 to 190tpa. The highest acidification potential is expected for those LBSs using BCS III, i.e. centralised fast-pyrolysis combined with a boiler-steam-turbine, causing an AP of between 214 and 241tpa. A small variation of around +/- 1 tonnes per year is estimated among the different biomass procurement areas, additionally indicating the great effect of the BCS in causing AP.

6.2.1.3 Eutrophication potential

Eutrophication is generally associated with environmental impacts involving excessively high levels of nutrients that lead to shifts in species composition and increased biological activity, for example, as algal blooms. In the LCA, the eutrophication category, sometimes also called nutrification, covers not only the impact of nutrients, but also those of degradable organic pollution and sometimes also waste heat, since they all affect biological productivity in some way (CML, 2002). These pollutants have one aspect in common, which is useful for characterisation modelling, i.e. they all lead to oxygen consumption. Discharges of degradable organic matter into water are broken down by micro-organisms, which consume oxygen, resulting in lower oxygen levels in the water and detrimental effects on aquatic ecosystems. Flows of nutrients as well as waste heat into the water lead to increased biological productivity and biomass formation, which in turn also lead to increased oxygen consumption when the biomass is being decomposed (Baumann and Tillman, 2004: 156). The causes of eutrophication are displayed in Figure 41, below:

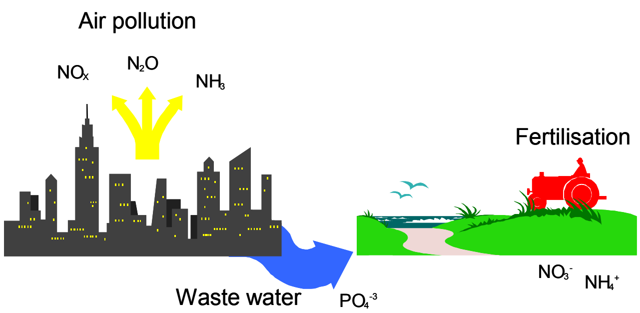

Figure 41: Impact pathways leading to eutrophication

Source: Heijungs et al. (1992)

Eutrophication is a phenomenon that can influence terrestrial as well as aquatic ecosystems. Nitrogen (N) and phosphorus (P) are the two nutrients most implicated in eutrophication. Other substances are rarely constraints. In most terrestrial ecosystems, the amount of nitrogen is the limiting nutrient and an increase of nitrogen will stimulate plant growth. In eutrophicated soils, an increased susceptibility of plants to diseases and pests is often observed, as is a degradation of plant stability. If the nitrification level exceeds the amount of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate. This can cause, by means of leaching, an increased nitrate content in groundwater (PE International, 2010). In aquatic ecosystems, phosphorus is normally the limiting factor for growth in fresh water, while nitrogen is the limiting factor in marine ecosystems. Nitrogen ending up in aquatic ecosystems comes from a number of different sources. Agricultural fertilisers and effluents from sewage works are major sources of nitrogen, but also parts of the atmospheric emissions of NO_x eventually end up in aquatic ecosystems (Baumann and Tillman, 2004: 156).

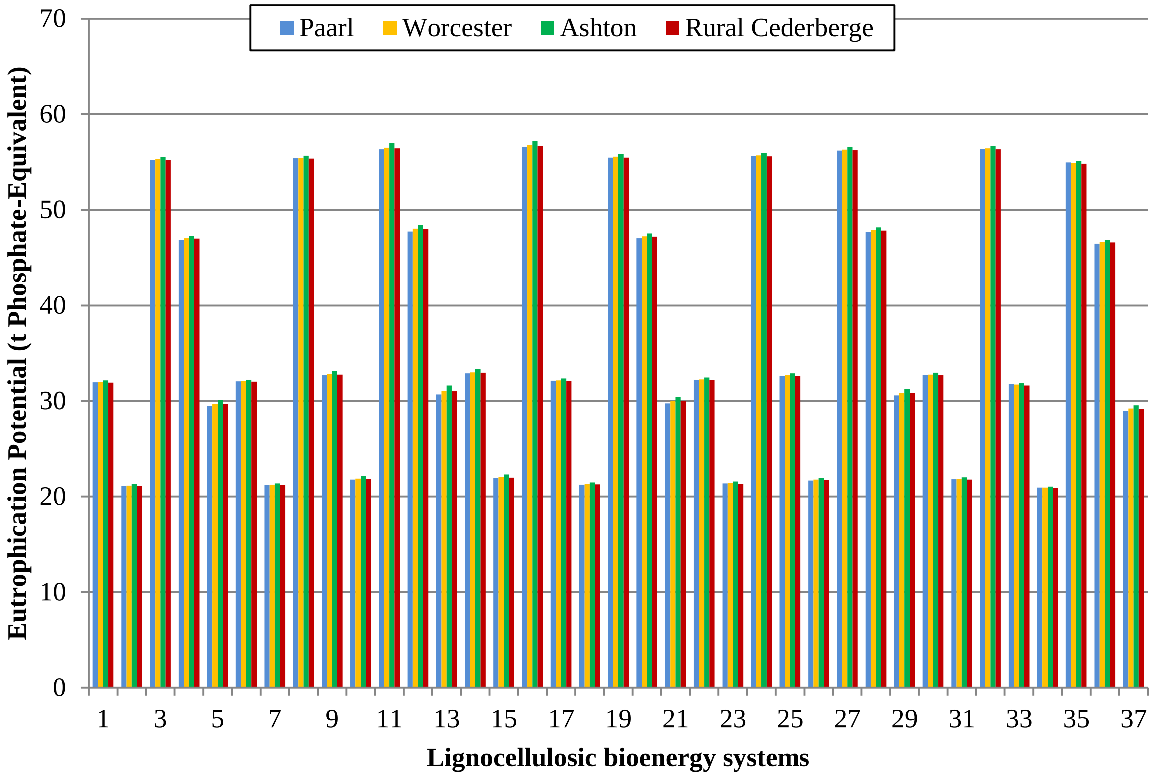

Figure 42: The LBSs' eutrophication potentials colour coded according to BPAs

For LBS key, refer to Figure 11

Since different ecosystems are limited by different nutrients, actual eutrophication varies geographically. As with acidification potential, this complicates characterisation, and the simplest solution is to disregard the geographical variation. Hence, eutrophication potentials reflect the maximum eutrophying effect of a substance. Maximum eutrophication assumes that all airborne nutrients eventually end up in aquatic systems, and includes all emissions of N and P substances to both air and water in the category together with emissions of organic matter (Baumann and Tillman, 2004: 156).

Eutrophication potential (EP) is expressed as a phosphate-equivalent (PO_4^{3-}), but given the molar ratios of the chemical formulae, phosphate-equivalents can easily be converted into NO_3 or O_2 equivalents. The EP of the different LBSs subdivided into biomass procurement areas is presented in Figure 42, above.

Similar to acidification potential, the greatest influence on this impact comes from the conversion systems, which account for more than 90% of eutrophication potential. This also explains the low variation of EP of around one tonne per year per LBS and biomass procurement area. Those LBSs using bioenergy conversion systems with a relatively high overall conversion efficiency show the lowest eutrophication potential, and vice versa. Hence, with higher overall conversion efficiency, less biomass and, therefore, less input in the value chain prior to the conversion is required, resulting in a relatively lower eutrophication potential.

6.2.1.4 Global warming potential

Climate change may lead to a broad range of impacts on ecosystems and our societies, but greenhouse gases (GHG) have one property in common, which is useful for characterisation in an LCA. Characterisation of GHGs is based on the extent to which they enhance the radiative forcing in the atmosphere, i.e. their capacity to absorb infrared radiation and thereby heat in the atmosphere (Baumann and Tillman, 2004: 149).

The mechanism of the greenhouse effect can be observed on a small scale, as the name suggests, in a greenhouse. These effects also occur on a global scale. Short-wave radiation from the sun reaches the earth’s surface and is partially absorbed and partially reflected as infrared radiation. The reflected fraction is absorbed by greenhouse gasses (GHGs) in the troposphere and is re-radiated in all directions, including back to earth. This results in a warming effect on the earth’s surface (PE International, 2010).

This effect is amplified by human activities, in addition to the natural mechanism. Carbon dioxide is not the only gas that causes climate change. Methane, chlorofluorocarbons (CFCs), nitrous oxide and other trace gases also absorb infrared radiation. Compared with CO_2, they absorb much more effectively. The potential contribution of a substance to climate change is expressed as its global warming potential (GWP) (Baumann and Tillman, 2004: 149).

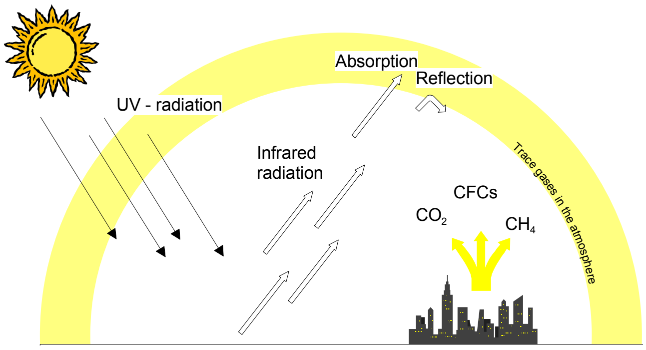

Figure 43: Impact pathways leading to greenhouse effect

Source: Heijungs et al. (1992)

Figure 43, above, shows the main processes of the anthropogenic greenhouse effect. GHGs are calculated in carbon dioxide equivalents (CO_2-equivalent), i.e. the greenhouse potential of an emission is given in relation to CO_2. Since the residence time of the gases in the atmosphere is incorporated into the calculation, a time range for the assessment must be specified, with a period of 100 years commonly being applied.

A distinction needs to be made between GHG emissions from fossil fuels and fuels from biotic sources. The former emit additional greenhouse gasses GHGs into the air, as the carbon has been stored over millions of years, whereas the latter take up carbon during its growth, via photosynthesis, resulting in a sequestration of carbon. Hence, when using biomass as a feedstock to generate energy, the CO_2-balance of the feedstock itself is zero. However, procuring biomass as well as, in some cases, negative carbon stock changes in soils cause additional GHG emissions. As long as bioenergy systems show lower GHG emissions than fossil-fuel energy systems, a substitution in terms of GHG emissions can be justified.

The LBSs' overall performance in terms of global warming potential is presented in Figure 44, below (for detailed results refer to Annexure 42). Comparatively, Ashton's LBS 27 has the greatest global warming potential ($GWP_{100years}$), with a CO_2-equivalent of 3 690t per year. The best-performing LBS in terms of $GWP_{100years}$ is no. 13 for the Paarl-BPA, which shows a net $GWP_{100years}$ balance of minus 36 448 tonnes per year. To put this in perspective, the South African Power-Grid Mix (SAPGM) has a $GWP_{100years}$ of 44 951 t CO_2-equivalent assuming the same functional unit (PE International, 2006 – refer to Annexure 38), i.e. even the LBS with the greatest $GWP_{100years}$ reaches only around eight percent of the SAPGM.

Significantly, different results can be seen for LBSs 5, 13, 21, 29 and 37. These alternatives have bioenergy system V in common, where only bio-oil produced in mobile fast-pyrolysis units is used for electricity generation. The other product from the fast-pyrolysis process, bio-char, is assumed to be sold to the fertilising industry for application to soil. Eighty percent of the bio-char is assumed to be stable in the soil, resulting in negative GWP levels of more than 32 000 t CO_2-equivalent across all biomass procurement areas for LBSs 5, 13, 21, 29 and 37.

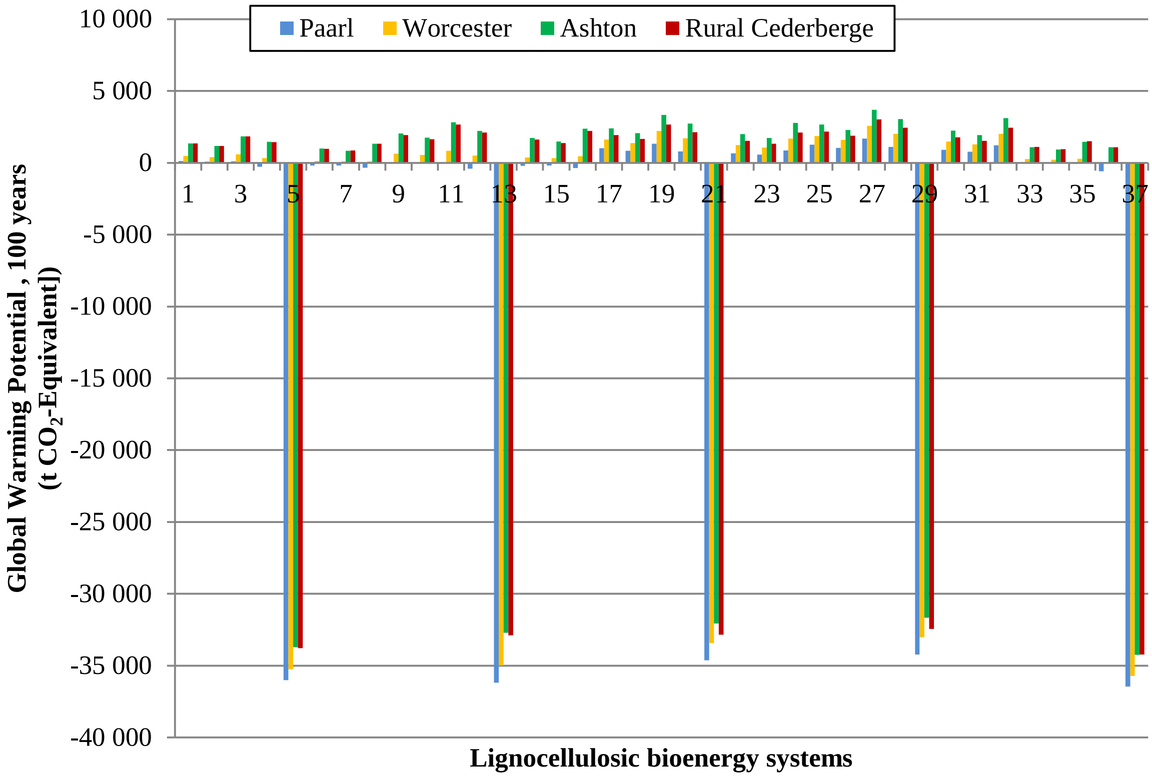

Figure 44: The LBSs' global warming potentials colour coded according to BPAs

For LBS key, refer to Figure 11

For the other LBSs, a similar observation can be made as for the acidification and eutrophication potential impact categories: the greater the overall-conversion efficiency of the bioenergy conversion system applied, the fewer up-stream activities are required and the lower the GWP. However, when comparing the GWP of an LBS for each biomass procurement area, significant variation can be found. This can be explained by the positive effects of carbon stock changes when introducing SRC plantations. As mentioned in section 3.3.3.3, primary biomass productivity is, *inter alia*, a function of rainfall. BPA I (Paarl) is characterised by a higher level of mean annual precipitation, resulting in a greater biomass productivity and carbon stock storage capacity compared with the other biomass procurement areas. Thus, some LBSs also show for BPA I (and II) a slightly negative net GWP, depending on whether the increase in carbon stock due to land-use change compensates for the GHG emissions caused during harvesting, forwarding, pre-processing and secondary transportation.

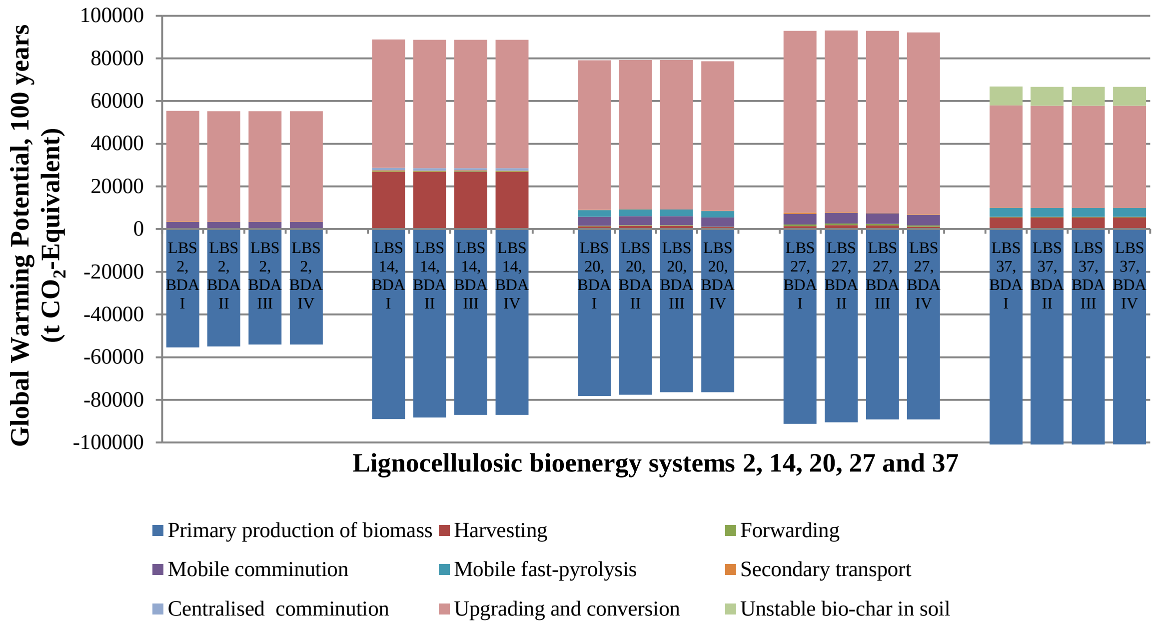

Figure 45: GWP of LBSs 2, 14, 20, 27 and 37 subdivided into production phases

For LBS key, refer to Figure 11

Figure 45, above, shows the performance of five selected LBSs (2, 14, 20, 27 and 37) per BPA in terms of GWP, subdivided into production phases. The first group (the first four bars) represents LBS 14, which uses bioenergy conversion system I; the second group, LBS 2, which uses BCS II. BCS III is the assumed conversion technology for LBS 27, represented by the third group of bars, followed by LBS 20, which uses BCS IV. The last group of bars in Figure 45 illustrates the $GWP_{100years}$ of LBS 37, which uses BCS V. For detailed results, refer to Annexure 2, Annexure 14, Annexure 20, Annexure 27, and Annexure 37.

The relatively large fraction of GWP for the harvesting phase for LBS 14 can be explained by the 30 percent of unutilised biomass remaining infield. Although there is no direct relation between the harvesting and decomposition of the unutilised biomass, it is during the harvesting phase that the trees are felled, de-branched and cross-cut, leaving the tops and branches behind. LBS 37 entails an unstable carbon fraction. When using biochar as additive to soil around twenty percent are assumed to be unstable, resulting in the decomposition thereof.

6.2.1.5 Photochemical ozone creation potential

Photo-oxidants are secondary pollutants found in the lower atmosphere, derived from NO_x (generic term for the mono-nitrogen oxides NO and NO_2) and hydrocarbons in the presence of sunlight. These substances are characteristic of photochemical smog, also known as summer smog, a known cause of health problems such as the irritation of respiratory systems and damage to vegetation (Baumann and Tillman, 2004: 153). Ozone is one of the most important photo-oxidants; others are peroxyacetyl nitrate (PAN), hydrogen peroxide, and various aldehydes. The smog phenomenon is crucially dependent on meteorological conditions and the background concentrations of pollutants. It can extend from being a local problem to one on a regional or even continental scale when emissions of NO_x and hydrocarbons are widespread and ozone is transported by wind (Harrison, 1990).

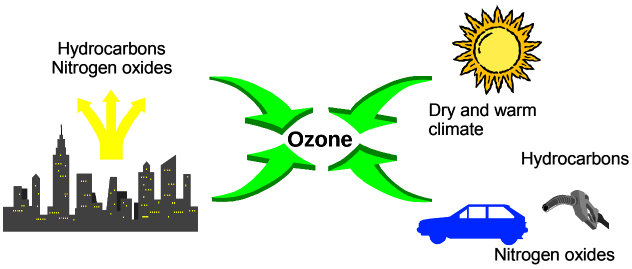

Figure 46: Impact pathways leading to photochemical Ozone Creation

Source: Heijungs et al. (1992)

Ozone is formed when NO_x and sunlight are present (refer also to Figure 46, above). Ozone production is increased when the air also contains organic substances. Different hydrocarbons react at different rates and efficiencies. In LCAs, photochemical ozone creation potential (POCP) is referred to in ethylene-equivalents (C_2H_4-equiv.). Noteworthily, when interpreting the POCP results, characteristics of local conditions and weather patterns should be considered.

Similar to the outcome of the impact categories acidification and eutrophication potential, Figure 47, below, shows that there is a strong relationship between the overall conversion efficiency of the LBSs and their respective photochemical ozone creation potentials. Those LBSs having relatively high overall conversion efficiencies show the least POC potential (between 5 and 11 t ethylene-equivalent per year), whereas those LBSs comprising BCS III, which are characterised by a relatively low overall conversion efficiency, show a POCP of 14 to 24 t ethylene-equivalent per year.

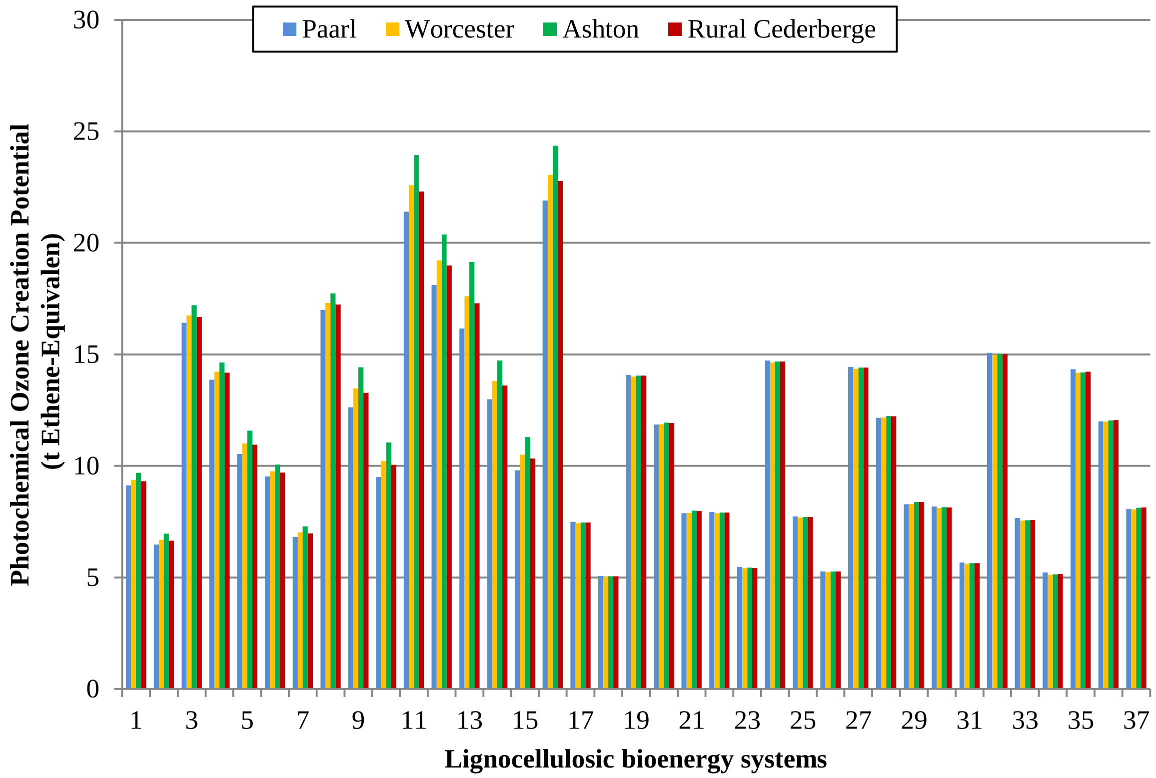

Figure 47: The LBSs' photochemical ozone creation potentials colour coded according to BPAs

For LBS key, refer to Figure 11

6.2.1.6 Toxicity

Toxicity is another complicated impact category, with a variety of characterisation methods. As yet, there is no coherent framework for characterising the toxicological impact pollutants, but research and methodology development in this area is in progress internationally (Baumann and Tillman, 2004: 151). They are considered troublesome impact categories for several political as well as scientific reasons. One has been the lack of inventory data for emissions, creating data gaps; others are linked to the models used and related data (Finnveden et al., 2009: 12).

A reason why the toxicity category is complicated is that it includes many types of impacts and substances. For example, organic solvents, heavy metals and pesticides all cause different types of toxic impacts. Some substances cause neurological damage; others are carcinogenic or mutagenic, among others. Toxic substances tend to spread: pesticides used for agriculture can end up in waterways, causing harm to aquatic organisms as well as making drinking water inconsumable. The toxicity category is therefore often divided into human toxicity and eco-toxicity (CML, 2002). Eco-toxicity, in turn, can be divided into aquatic toxicity and terrestrial toxicity. Furthermore, aquatic toxicity can be divided into freshwater and marine toxicity (Baumann and Tillman, 2004: 151).

The CML 2001 (Nov 09) impact assessment collection comprises four toxicity impact categories:

- Human toxicity potential (HTP) [kg Dichlorobenzene (DCB)-equivalent]
- Terrestrial ecotoxicity potential (TETP) [kg DCB-equivalent]
- Freshwater aquatic ecotoxicity potential (FAETP) [kg DCB-equivalent]
- Marine aquatic ecotoxicity potential (MAETP) [kg DCB-equivalent]

However, toxicity impact categories are not included in this study due to a lack of consistency in the field for hazardous substances and heavy metals (Gediga, 2011), potentially resulting in incorrect conclusions stemming from inconsistent data. In addition, and partially as a result of this lack of consistency, the characterisation factors for toxicity impacts will change due to further development and refinement of the methodology. To highlight the inconsistency, Table 47, below, shows the terrestrial ecotoxicity potential for two power-grid mixes for LBS 1 (BPA I), based on the functional unit, i.e. 39.6 GWh/year.

Table 47: Terrestrial ecotoxicity potential for various power-grid mixes

	Terrestrial ecotoxicity potential (TETP) in t DCB-equivalent/functional unit (39.6 GWh/year)		
	South Africa Power-Grid Mix	Great Britain Power-Grid Mix	Bioenergy alternative 1, BPA I
CML 96	75 928	25 984	1 549
CML 2001 (Nov. 2009)	146	19	1

Source: PE International (2006)

6.2.2 Other environmental impacts

A general discussion on the impact of lignocellulosic bioenergy systems on biodiversity and water balance is given below.

6.2.2.1 Impact on biodiversity

Biological diversity, normally referred to as biodiversity, is defined by the United Nations Convention Biological Diversity (UNCBD, 1973) and the Millennium Ecosystem Assessment Board (MEA, 2005) as: “the variability among living organisms from all sources including, *inter alia*, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems”. The term is used to cover all forms of life, but for practical purposes, it is often used in reference to specific taxa, e.g. biodiversity of plants, biodiversity of mammals, biodiversity of insects, and others. In its most common usage it refers to the disappearance or decrease in abundance of naturally occurring (endemic or indigenous) species that are implied when 'loss of biodiversity' is being discussed (Von Maltitz et al., 2010). When considering biodiversity, it is often convenient to subdivide the landscape into units of similar biodiversity, such as habitat types or ecosystems. The habitat type is typically defined by eco-regions, biomes or broad vegetation type such as lowland forest, dry deciduous forest, grassland, wetlands when working at a global or national level, but it could be a more detailed local classification when working at a plantation level (Von Maltitz et al., 2010).

Biodiversity is important in all ecosystem services, directly or indirectly, although the relationship is often quite complex and subtle. There is firm evidence that diverse ecosystems, in general, are both more productive and more resilient to stress than less diverse ecosystems (MEA, 2005).

Figure 48, below, shows the pathways and processes by which biodiversity influences ecosystem services, and ecosystem services influence human wellbeing. The value of supporting services, most of the value of regulating services, and most of the aspects of biodiversity are contained within the value of the directly used provisioning and cultural services. These underlying elements can influence the direct services through altering the mean magnitude of the service (μ) or its variability in time (σ) or its variability in space (γ) (Amezaga et al., 2010: 85).

The deliberate simplification of ecosystems, for instance, through mechanised monocultural cropping using high inputs of nutrients, water and pesticides has been the key mechanism for increased provisioning services such as food and fuel over the past century. This has generally been at the cost of other services – even of other provisioning services – such as water and biodiversity (MEA, 2005). Biofuel expansion, if not carefully regulated, has the potential to have very high impacts on biodiversity, especially as a consequence of habitat loss. It is counter-productive to fight one global environmental problem – climate change – and simultaneously exacerbate a second global environmental problem by increasing biodiversity loss. This is, however, a complex trade-off, since climate change is also predicted to have profound impacts on biodiversity (Thomas et al., 2004).

Changes in temperature and rainfall regimes will displace habitats. The predicted rise in temperatures will displace the zone of climate preference for most species polewards or to higher altitudes. It is likely that a significant fraction of species will lose their current habitats completely, and will thus ultimately become extinct unless steps are taken to intervene (Hannah et al., 2002; Thomas et al., 2004). Though biofuels can mitigate climate change impacts in part, this positive impact is likely to be very small compared with the high negative land transformation costs. The synergistic impact of both land transformation and climate change will be a double blow to biodiversity, with transformed habitats making it much harder for species to adapt to climate change (Von Maltitz et al., 2010).

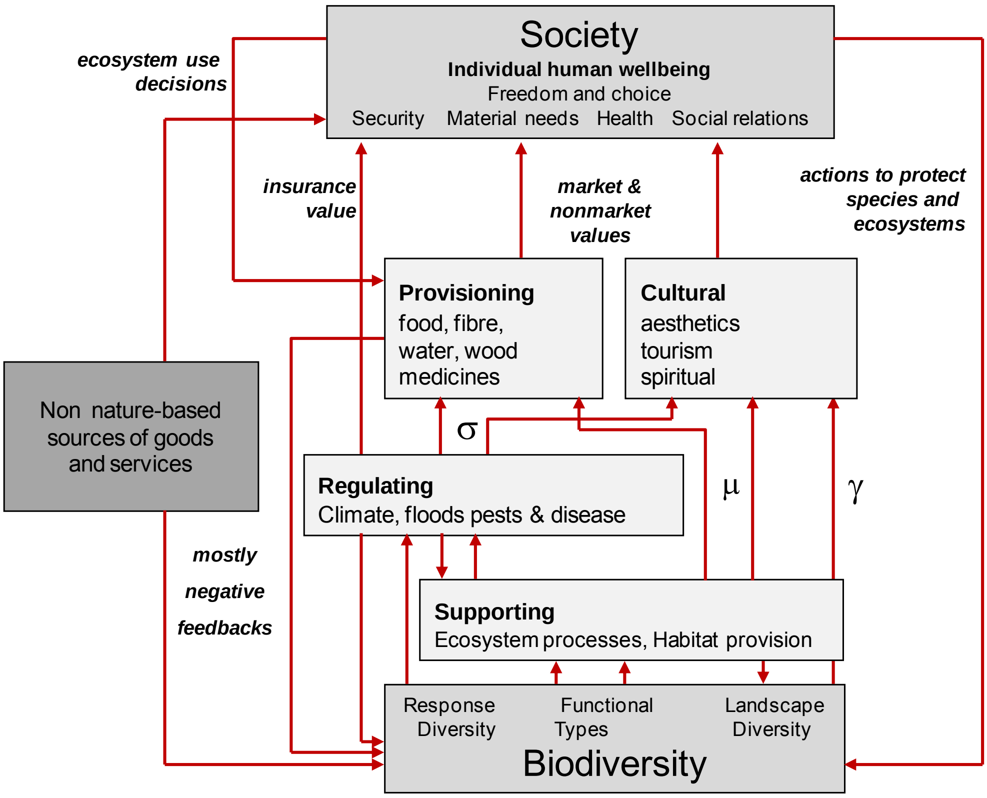

Figure 48: Influence of biodiversity on ecosystem services

Source: Von Maltitz et al., 2010: 85)

Two aspects underpin the severity of biodiversity impacts. One is the importance of the habitat for biodiversity protection, and the other is the degree to which the proposed land is degraded or already transformed. A simple matrix (Von Maltitz et al., 2010) illustrates that it is untransformed areas of high biodiversity importance that are likely to have the greatest biodiversity conservation value (see Figure 49, below).

A potential approach in determining the impact on biodiversity due to land-use change is the biodiversity intactness index (BII). The BII is a measure of the change in abundance across a wide range of well-known elements of biodiversity, relative to their levels in a chosen reference case. It is an indicator of the average abundance of a specified set of organisms (or functional groups of organisms) in a given geographical area. The BII is intended to provide a single, integrated measure of biodiversity, and the principles underlying the BII are discussed in Scholes and Biggs (2005) and

Biggs (2005). The application of the BII, however, would have gone beyond the scope of this study, and therefore, it has not been included.

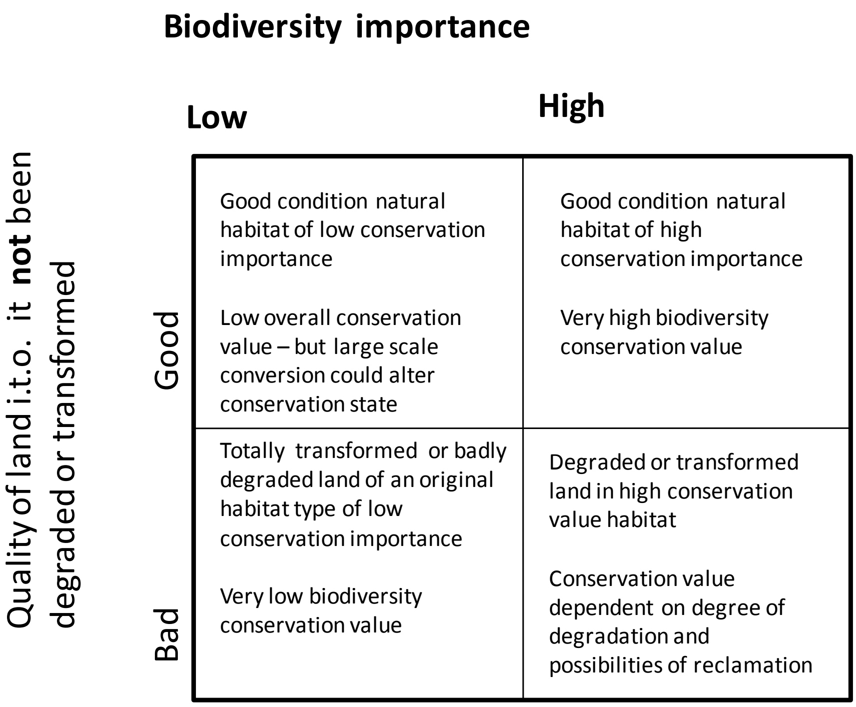

Figure 49: Determining conservation importance as a function of both habitat quality and level of degradation of the natural habitat

Source: Von Maltitz et al. (2010: 92)

For this study, another approach aimed at minimising the impact on biodiversity has been applied. In a previous study (refer to Von Doderer, 2009: 9-28), suitable land for biomass production in the CWDM was identified by means GIS. Ecologically sensitive areas, such as protected areas (e.g. nature reserves, national parks), critical biodiversity areas, water catchment areas, waterbodies and wetlands and other sensitive areas from ecological and aesthetical points of view, as identified by an expert group, were amongst other unsuitable land use types excluded.

6.2.2.2 Water balance

Natural capital – air, land, habitats and water – is essential for the natural environment, which performs functions essential for human existence and life on earth (Costanza and Daly, 1992), such as providing biomass. The availability of fresh water is a prerequisite for the growth of biomass. Solar radiation is the principal driving force behind the evaporation of water (Gerbens-Leenes et al., 2009: 1055).

Various concepts and tools have been developed to determine the water requirements of crops, for instance, CROPWAT, a FAO-developed computer programme for farmers, for irrigation planning and management (FAO, 2011, Allen et al., 1998); or the water footprint (WF) concept introduced by Hoekstra and Hung (2002), who define the WF as the total volume of fresh water used to produce the goods and services related to certain consumption patterns. The WF of a product (commodity, good or service) is defined as the volume of fresh water used for the production of that product at the place where it was actually produced (Hoekstra and Chapagain, 2008). Most of the water used is not contained in the product itself. In general, the actual water content of products is negligible compared with their WF (Gerbens-Leenes et al., 2009).

An assessment has been done by Gerbens-Leenes et al. (2009) of the WF of energy from biomass, and the related consequences of an increasing share of bioenergy in the supply of energy. Various primary energy carriers derived from biomass are expressed as the amount of water consumed to produce a unit of energy (m^3/GJ), showing considerable differences among the WFs for specific types of primary bioenergy carriers. The WF depends on the crop type, agricultural production system, and climate. The WF of biomass is 70 to 400 times larger than the WF of other primary energy carriers (excluding hydropower).

Water balance is a location-specific issue, but is likely to be a constraining factor, particularly in the future, when climate change will have a severe impact on agricultural and other activities.

However, although likely to be a constraining factor, the WFs of the bioenergy systems in this study have not been included, since WF is a location-specific issue. Areas not meeting the minimum water requirements were excluded a priori in the land availability assessment by applying the so-called aridity index (Von Doderer, 2009).

In some cases, the introduction of SRC plantations may have a positive effect on the water balance, e.g. when replacing intensive agriculture under irrigation or when establishing SRC plantations on land that is infested with so-called undesired alien invader plants (AIPs).

6.3 Financial-economic criteria

Budgeting is perhaps the most widely used method of financial planning. Budgeting, as a non-optimising method, evaluates plans in physical and financial terms (Hoffmann, 2010). The popularity of budgets stems from their simplicity of use and the fact that they aid in the heuristic approach to decision-making, rather than imposing an analytic framework on the decision maker (Rehman and Dorward, 1984: 181). Budgets are often used as comparable quantitative techniques and play an important role in benchmarking.

Budgeting methods have been employed since the inception of agricultural economics and extension. During this time, standard accounting methods have been employed to generate comparable information for analyses and to serve as benchmarking information. Since budgeting is considered straightforward and practical, not much attention is given to it in the academic literature (Malcolm, 1990: 35).

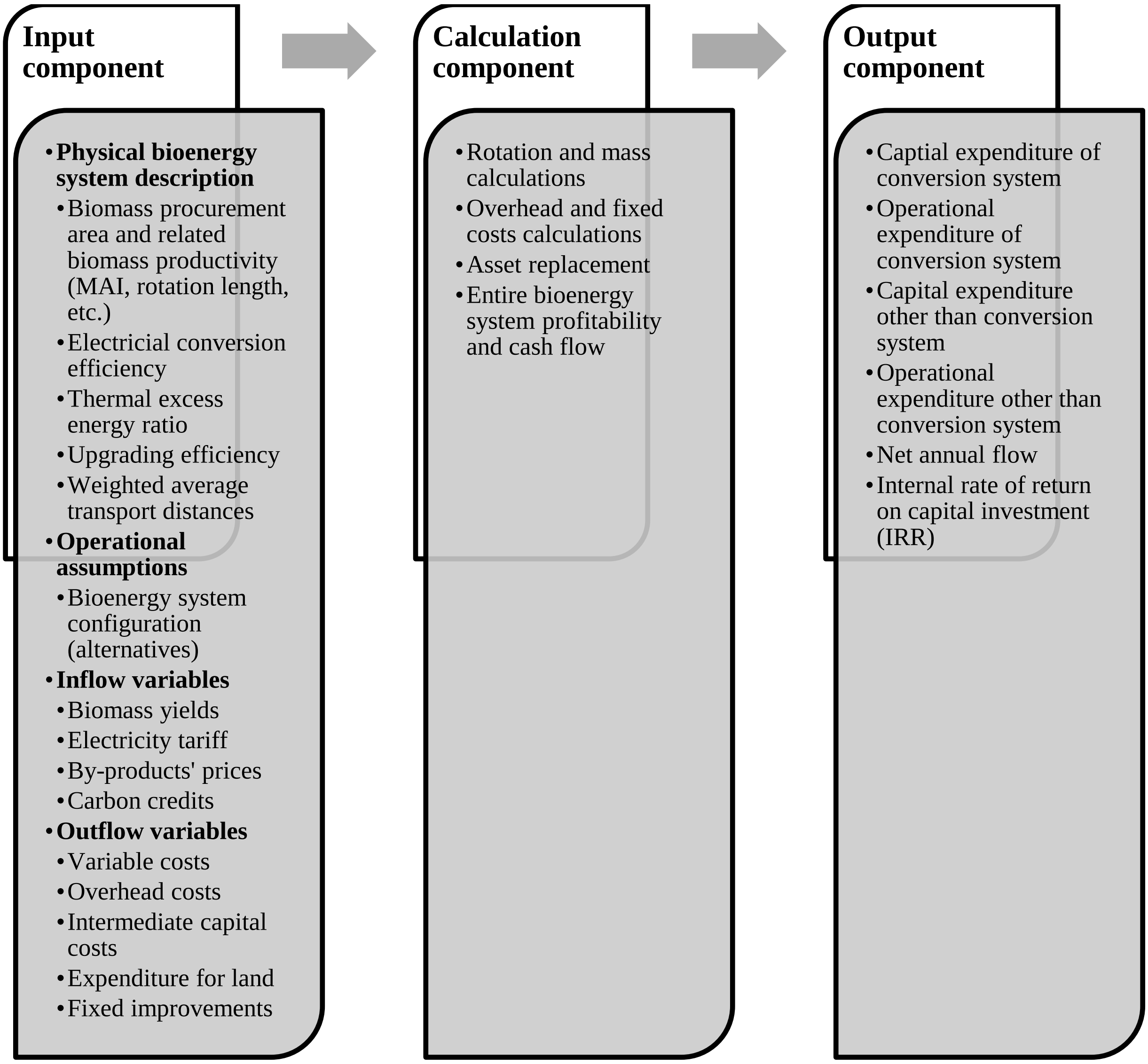

Figure 50: Graphic representation of multi-period budget model components for bioenergy systems

Budget models are, in essence, simulation models, normally developed using spreadsheet programs, where complex and sophisticated calculations and relationships can be expressed in a relatively simple way. The sophistication of budget models lies in their ability to allow for detail, adaptability and user-friendliness (Keating and McCown, 2001). Incorporating physical as well as financial parameters, budgets usually generate information on profitability such as net income or cash flow. With some adaptation, system budget models may also be extended over time to calculate returns on capital invested and to calculate profitability indicators such as the internal rate of return on capital investments (IRR) or net present value (NPV).

The components of the calculation model are shown below in Figure 50. This figure illustrates the input component (refer also to Chapters 2, 4 and 5), calculation component and output component of the multi-period budgeting (MPB) model. Each component consists of various parts. More information on the concept of MPB or farm modelling can be found in Hoffmann (2010) or Strauss (2005).

6.3.1 Internal rate of return

A common measure of profitability or project worth in investment analysis is the internal rate of return (IRR), expressed as a percentage, where the incremental net benefit stream or incremental cash flow is used to measure the worth of a project. This is done by finding the discount rate that makes the net present value of the incremental net benefit stream or incremental cash flow equal to zero. It is the maximum interest that a project could pay for the resources used if the project were to recover its investment and operating costs and still break even (Gittinger, 1982: 329; Reilly and Brown, 1997: 529, 1058).

The performance of each LBS per biomass procurement area in terms of IRR is illustrated in Figure 51 (refer also to Annexure 45), below, showing significantly different results for each. LBS 34 shows the best IRR across all biomass procurement areas, with 11.18%, 15.26%, 10.13% and 8.25% for BPAs I, II, III and IV respectively. This can be explained by the relatively high overall conversion efficiencies of BCS II, as well as by the high harvesting system efficiencies of the modified combine harvester. The LBSs employing BCS II show on average – with one exception (No. 15) – IRRs of around ten percent across all BPAs.

LBS 11 shows the least favourable results in terms of IRR: For BPA I, the IRR was so negative that no result was given in the spreadsheet-based MPB model. BPAs II-IV also give a negative outcome, with -2.00%, -4.32% and 2.83% respectively. This can be explained by the relatively low overall conversion efficiencies, together with the low harvesting efficiencies, due to the motor-manual harvesting and manual loading and unloading of logs onto the tractor-pole-trailer combinations, leaving 30% of the biomass in form of branches and tops behind. In general, LBSs employing BCS III exhibit negative to marginally positive IRRs.

Similar to most environmental impact category criteria, when using the same harvesting system, LBSs employing BCS II show the best comparative results, followed by BCS I, BCS V, BCS IV and BCS III. LBSs 33-37, which are characterised by their high degree of mechanisation in terms of harvesting system, show more favourable results than, for instance, LBSs 9-16, which have the lowest degree of mechanisation.

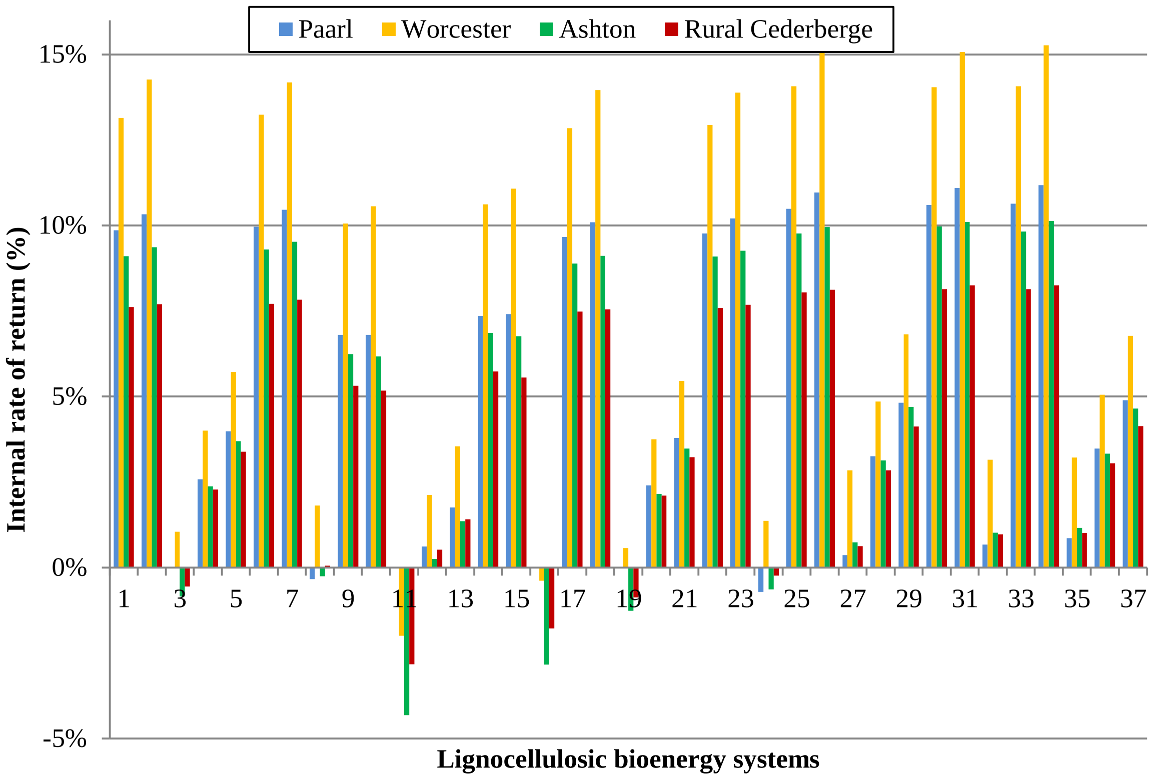

Figure 51: The LBSs' internal rate of return (including land value) colour coded according to BPAs

For LBS key, refer to Figure 11

When comparing the LBSs, significant differences between the biomass procurement areas can be seen. The Worcester biomass procurement area (BPA II) yields generally better results than the other biomass procurement areas, followed by BPAs I, III and IV. This can be explained by the relationship between land value, land productivity and rotation length of the SRC plantations per biomass procurement area.

Typical land values for each of the BPAs were obtained from Adval Valuation Centre (2011) – refer also to Von Doderer and Kleynhans (2010). Data on biomass productivity per hectare and rotation length for each BPA can be found in section 3.3.2.

BPA I (Paarl) has the highest productivity (MAI 27 t/ha/a, fresh biomass) and the shortest rotation length (five years), but is also characterised by the highest land value of R50 000 per hectare, due to the great demand for it and its competition with other land use activities. BPA II's land value, at R8

000/ha, is considerably lower than BPA I's land value, but it still has a reasonably good annual productivity of 18 t/ha/a and a seven-year rotation length. A land value of R5 000/ha, a MAI of 9 t/ha/a, and a rotation length of ten years is suggested for BPA III (Ashton). Due to BPA IV's remote location (Rural Cederberge), as well as the generally low agricultural productivity of the land, its value is relatively low – R1 000/ha – but so is its biomass productivity, at 5 t/ha/a, resulting in a relatively long waiting period of 15 years until harvesting.

The effect of the land value becomes apparent when comparing Figure 51, above, with Figure 52, below. The latter shows the IRR of the LBSs excluding the land value (refer also to Annexure 46). LBS 34 still proves to be the best-performing alternative in terms of IRR, resulting in yields of 26.57%, 20.00%, 13.16% and 9.03% for BPAs I-IV respectively. LBS 11, proving to be the least favourable in terms of IRR, shows a positive 0.69% for BPA I, but remains negative for the other BPAs, with -0.87%, -3.52% and -2.61% respectively.

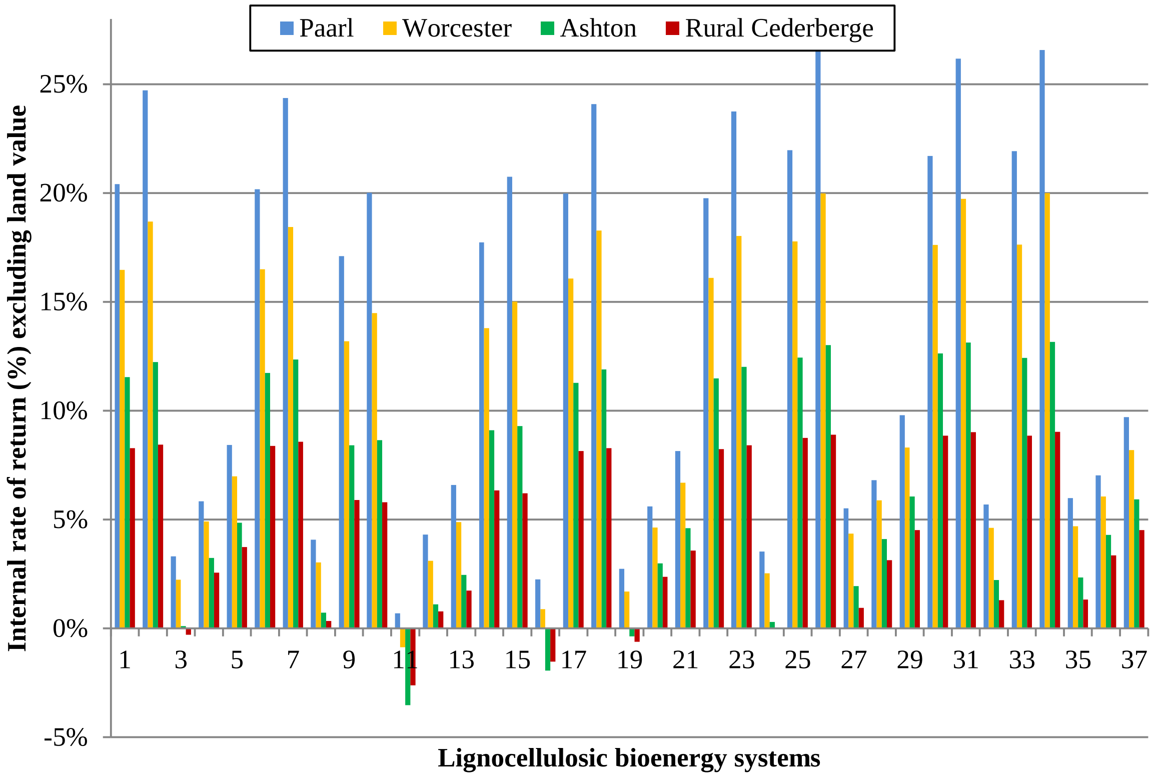

Figure 52: The LBSs' internal rate of return (excluding land value) colour coded according to BPAs

For LBS key, refer to Figure 11

6.3.2 Cost of technology for biomass upgrading and conversion

Since both the capital expenditure and operating expenditure of the bioenergy conversion systems contribute largely to the overall performance in terms of profitability of each LBS, they are discussed separately. The investment in biomass upgrading and bioenergy conversion technologies is a venture that requires an assessment of possible technology types and providers, *inter alia*, in terms of product to be produced, conversion efficiency, how well the technology is established, the degree of mechanisation and integration, and the related capital and operational expenditures. Different upgrading and conversion technology options and their properties are discussed in section 4.3.1.7. The selected five bioenergy conversion systems (BCS) are described in detail in section 5.8, taking general characteristics, financial-economic and environmental criteria into consideration.

6.3.2.1 Capital expenditure

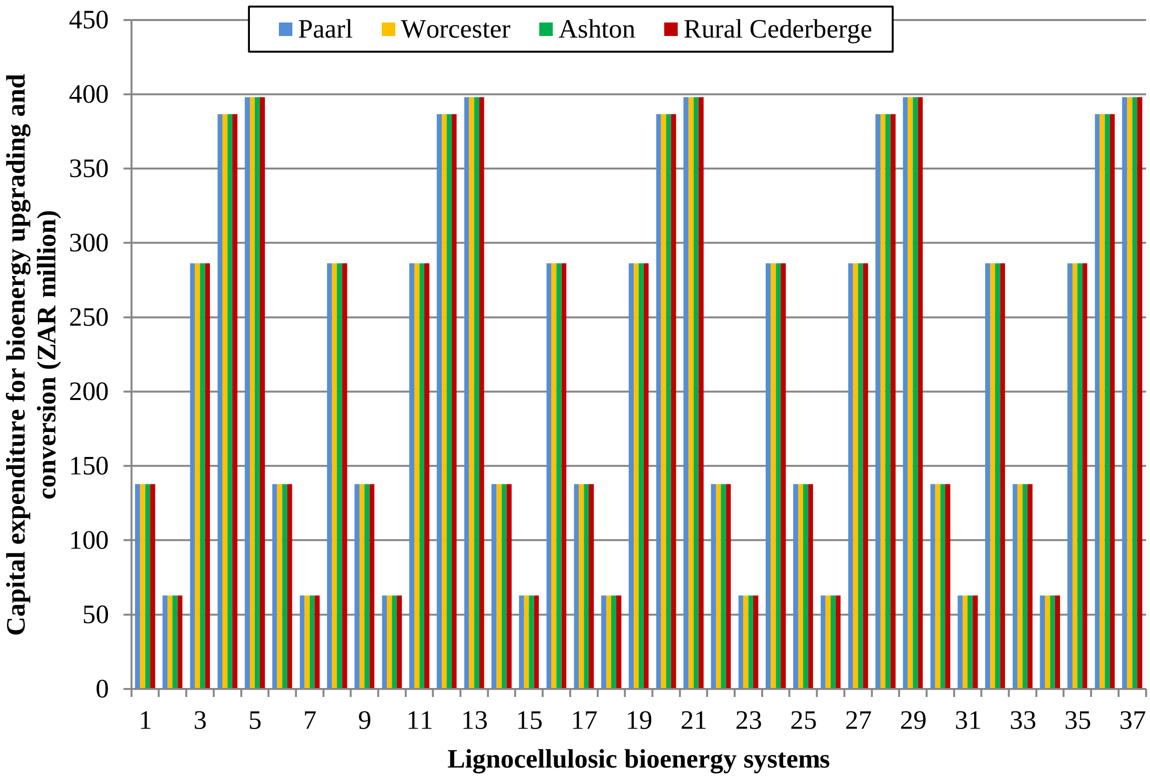

Figure 53: Capital expenditure of biomass upgrading and bioenergy conversion systems

For LBS key, refer to Figure 11

The establishment of a bioenergy conversion system represents a capital intensive venture, carrying a significant risk. The BCS factors contributing to this risk are, *inter alia*, a sufficient supply of feedstock, continuity of production, reliability of the conversion technology and all ancillary systems, and a guaranteed market for the products produced. In the case of BCSs, the risk is normally carried by either a single or a few private investors, a public investor, or a joint venture between the public and private sectors. Investors from the private sector, particularly, are expected to have a great short-term interest not only in the maximisation of their return on investment (ROI) but also in the sustainable development of their investment. Public investors, on the other hand, may not have the maximisation of ROI as their priority, but rather an interest in the sustainable creation of employment opportunities, as well as the sustainable supply of energy. Hence, public investors may not seek the most profitable alternative, but may take the opportunity costs into account, in order to create jobs, infrastructure and to ensure a reliable energy supply.

Figure 53 shows the CAPEX required for the biomass upgrading and bioenergy conversion systems ($CAPEX_{conversion}$) for each LBS (refer also to section 4.8.2 and to Annexure CAPEX-C). As mentioned above, five types of biomass upgrading and conversion combinations were considered, with LBSs employing BCS II being the least $CAPEX_{conversion}$ intensive (R62.9 million). BCS I comes second (R137.8 million), followed by BCSs III, IV and V (R286.3 million, R386.6 million and R398.0 million respectively). The considerably higher $CAPEX_{conversion}$ for LBSs employing BCS IV and V can be explained by the great numbers of mobile fast-pyrolysis units required, which are relatively costly, as the technology is still relatively immature at this stage. Also, unlike the stationary upgrading and conversion systems, which can be in production for 24 hours a day, the mobile fast-pyrolysis units are assumed to convert biomass into bio-oil and bio-char during two shifts per day (16 hours), resulting in a greater number of units required.

The costs of property and ancillary infrastructure have not been taken into account, resulting in an equal $CAPEX_{conversion}$ of the bioenergy conversion systems for each LBS across all biomass procurement areas.

6.3.2.2 Operating expenditure

The operating expenditures of the bioenergy conversion systems ($OPEX_{conversion}$) for each LBS, over an economic lifetime of 20 years, are shown in Figure 54, below. As for the $CAPEX_{conversion}$, no distinction was made in terms of costs for the different biomass procurement areas. Although the degree of automation of BCS II is relatively low, which may result in increased operating cost, LBSs employing BCS II still show the lowest operating cost. Again, the second best BCS is no. I, followed by BCS III. BCS V employs a direct-injection gas-turbine only, using bio-oil as a feedstock, which requires a greater degree of automation, resulting in lower operating costs compared with BCS IV. Detailed results for annual operating costs can be found in Table 39, above, or in Annexure 49.

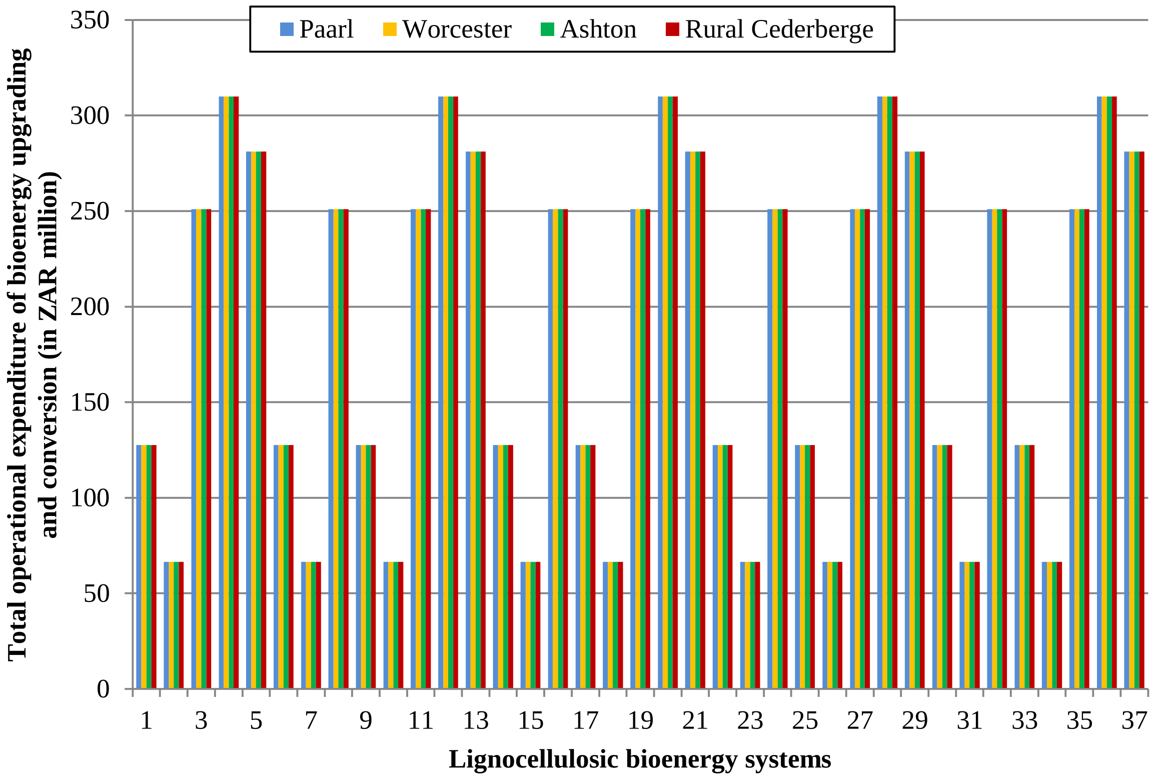

Figure 54: Operating expenditure for biomass upgrading and bioenergy conversion systems

For LBS key, refer to Figure 11

6.3.3 Cost other than conversion technology

Costs other than those for the conversion technology include all expenses along the value chain prior to biomass upgrading (i.e. fast pyrolysis) and bioenergy conversion, i.e. from land value, primary production of biomass, harvesting, forwarding, comminution, secondary transport, amongst others. In contrast with the costs of the conversion systems, which are expected to be carried by a single investor or a limited number of investors, the costs occurring during the other production phases are carried by a variety of investors, such as land owners and entrepreneurs. All operations prior to upgrading and conversion, for instance, could be taken care of by contractors specialising in the harvesting of SRC plantations, forwarding, comminution, or secondary transport. As for the IRR, the time period taken into consideration differs from BPA to BPA, taking the economic lifetime expectancies of the conversion units plus one rotation length into account to ensure a continuous supply of biomass. Thus, 25, 27, 30 and 35 years are assumed for BPAs I, II, III and IV respectively.

6.3.3.1 Capital expenditure

Capital expenditures other than those of the bioenergy conversion systems ($CAPEX_{other}$) for each LBS and biomass procurement area are illustrated in Figure 55, below (for detailed results refer to Annexure 50). Significantly higher $CAPEX_{other}$ can be seen for the biomass procurement area Paarl, which can be explained by the 50 times greater land value than for BPA IV (Rural Cederberge). Furthermore, the weighted average transport distances for BPA I are more or less double those of the other biomass procurement areas, resulting in significantly higher secondary transport costs. In general, as discussed in section 5.31, the total land costs for producing biomass in an SRC system are a function of the land value per hectare, the biomass productivity, and the rotation length. The effect of these costs is considerable, therefore, also affecting profitability.

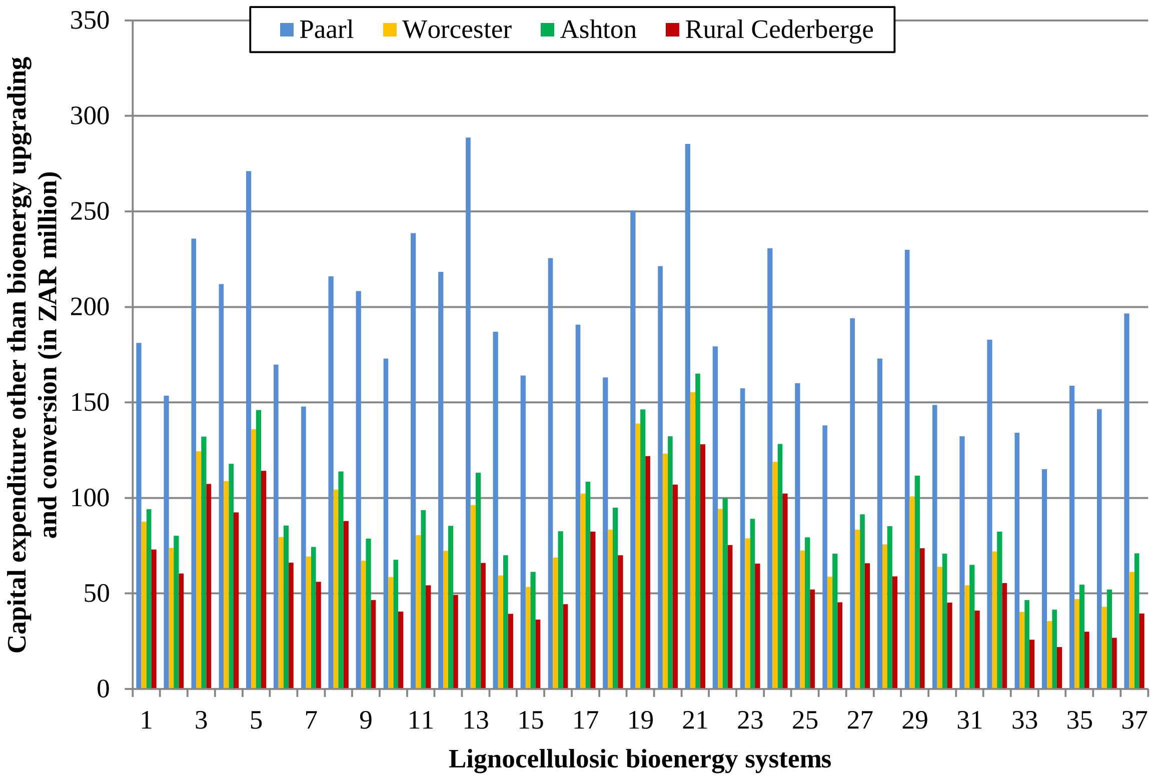

Figure 55: Capital expenditure other than for conversion systems

For LBS key, refer to Figure 11

When comparing the LBSs with one another, a similar picture as for the IRR can be seen. LBS 34 shows the lowest requirement $CAPEX_{other}$ across all biomass procurement areas, which can be explained by the relatively good overall conversion efficiency, resulting in less biomass being required, as well as the relatively low unit costs of the harvesting system. A more complex result is obtained for the highest $CAPEX_{other}$: in BPA I, LBS 13 has the highest $CAPEX_{other}$, since it requires the most biomass prior to harvesting, due to losses during harvesting (30% of the biomass remains in-field), losses during comminution (less 5%), and due to the fact that only bio-oil is used in generating electricity. Hence, for the primary biomass production, more than 5 000 hectares are required to ensure a continuous supply of energy feedstock, resulting in a total land value of more than R250 million, and causing a total $CAPEX_{other}$ of almost R290 million. In BPA I, a difference of about R3 million exists between LBSs 13 and 21. Although the latter initially requires less biomass, and therefore less land, the MPB model shows that for LBS 21 more investment in intermediate capital equipment, such as three-wheelers, forwarders, and mobile-chipping units is necessary. This is also why LBS 21 comes first in terms of $CAPEX_{other}$, of R155m, R165m and R128m respectively, for the other biomass procurement areas.

6.3.3.2 Operating expenditure

Operating expenditure other than for conversion systems ($OPEX_{other}$) includes all operating costs prior to biomass upgrading and bioenergy conversion, such as primary biomass production, harvesting, forwarding, comminution and secondary transport. The results for $OPEX_{other}$ are illustrated in Figure 56.

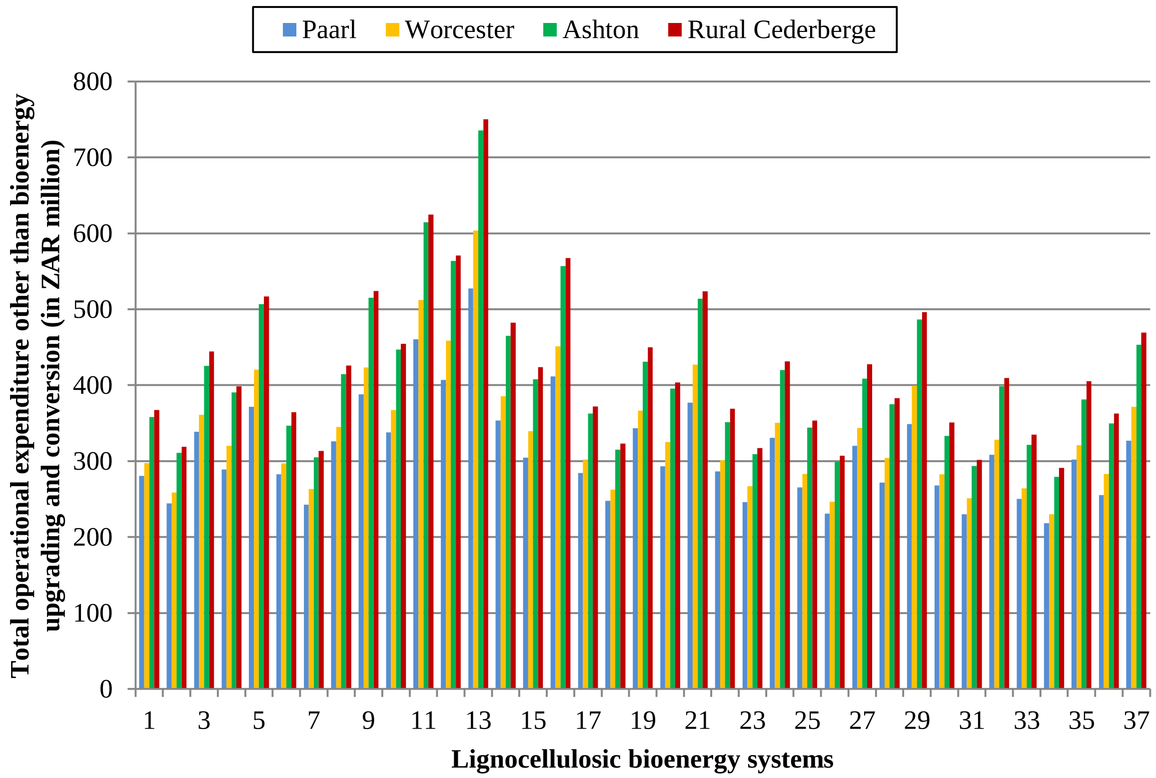

Figure 56: Operating expenditure other than for conversion systems

For LBS key, refer to Figure 11

As for $CAPEX_{other}$, the LBS with the lowest $OPEX_{other}$ is LBS 34, which can be explained by the same reasons as those in section 5.3.1. Again, LBS 13 exhibits the least favourable results. However, when comparing each LBS, a different picture emerges. Whereas for $CAPEX_{other}$ BPA I shows comparatively higher costs, mainly due to the cost of land, for $OPEX_{other}$ BPA I has the lowest value. This can be explained by the relatively higher biomass productivity per hectare, resulting in the lowest land requirements. Vice versa, BPA IV, has the lowest biomass productivity and the longest rotation length, requiring considerably more land to ensure a continuous supply of biomass. This means, for instance, that more land needs to be prepared and more SRC plantations need to be established, as well as maintained.

6.4 Socio-economic criteria

Biomass utilisation, bioenergy technologies, their market share, and research interests in these issues vary considerably among countries. Nevertheless, in most of the countries, the socio-economic benefits of using bioenergy can clearly be identified as a significant driving force in increasing the share of bioenergy in the total energy supply. In most countries, regional employment created and economic gains are probably the two most important issues regarding using biomass to produce energy (Domac et al., 2005: 98).

Table 48: Benefits associated with local bioenergy production

Dimension	Benefit

Social aspects	• Increased standard of living
	  ○ Environment
	  ○ Health
	  ○ Education
	• Social cohesion and stability
	  ○ Migration effects (mitigating rural depopulation)
	  ○ Regional development
	  ○ Rural diversification

Macro economic level	• Security of supply/risk diversification • Regional growth • Reduced regional trade balance • Export potential
Supply side	• Increased productivity • Enhanced competitiveness • Labour and population mobility (induced effects) • Improved infrastructure
Demand side	• Employment • Income and wealth creation • Induced investment • Support of related industries

Source: Madlener and Myles (2000)

The essence of the sustainability of bioenergy projects from a social perspective is how they are perceived by society, and how different societies benefit from these activities (refer also to Table 48, below). Avoiding carbon emissions, environmental protection, security of energy supply on a national level, or other 'big issues' are added bonuses for local communities in pursuing these projects, but the primary forces are much more likely employment or job creation, contribution to the regional economy, and income improvement. Consequently, benefits such as these that stem from the introduction of an employment and income generating source will result in increased social cohesion and stability (Domac et al., 2005: 98).

The introduction of bioenergy systems could also help to mitigate adverse social and social cohesion trends (e.g. high levels of unemployment, rural depopulation, among others.), having positive effects on rural labour markets by, firstly, introducing direct employment and, secondly, supporting related industries and employment in these.

Demand side effects constitute the focal point of the majority of socio-economic impact studies, and are concentrated on for several reasons. Most notably, they are relatively easy to define and the scale of the investment's impact can be quantified with reasonable accuracy. Moreover, it is the economic impact that is most important to regional developers and decision makers (Domac et al., 2005). Thus, since an entire social impact assessment (SIA) would have gone beyond the scope of this study, a simplified approach was used to determine the socio-economic impact, i.e. by focussing on the direct employment opportunities offered by each LBS. Indirect employment opportunities, the mitigating effects of rural depopulation, and other socio-economic criteria were not captured. However, more information on the assessment of social impacts of bioenergy projects can be found, *inter alia*, in Tiwari et al. (2010) and Ngepah (2010).

6.4.1 Direct employment creation potential

Direct employment results from operation, construction and production. In the case of bioenergy systems, this refers to the total labour necessary for the crop production, harvesting and pre-processing, and transportation of the biomass, as well as the construction, operation, and maintenance of the conversion plant (Domac et al., 2005: 102). As for the LCA (refer to section 4.8.1), the building and commissioning of conversion plants is not included in determining potential.

Current levels of unemployment for the CWDM are given in Table 1, indicating a current unemployment rate of around 20 percent. Figure 57, below, shows the unemployment rate between 1995 and 2007 in terms of level of education (in years) for South Africa (SA), as well as for the

Western Cape province (WC) (Burger, 2011). Although significantly lower compared with the national average, the WC's unemployment rate for unskilled to semi-skilled labourers is still remarkably high, with more than one out of five being unemployed. With an increase in level of education, particularly of tertiary education, the risk of unemployment reduces significantly. This also results in South Africa having one of the most unequal income distributions in the world. Much of this inequality derives from the large wage disparities between workers of different skill groups (Burger, 2010). The latter is well illustrated in Figure 58, below, which shows the mean monthly earnings in terms of level of education for the South African average, and in comparison with the agricultural sector in the Western Cape.

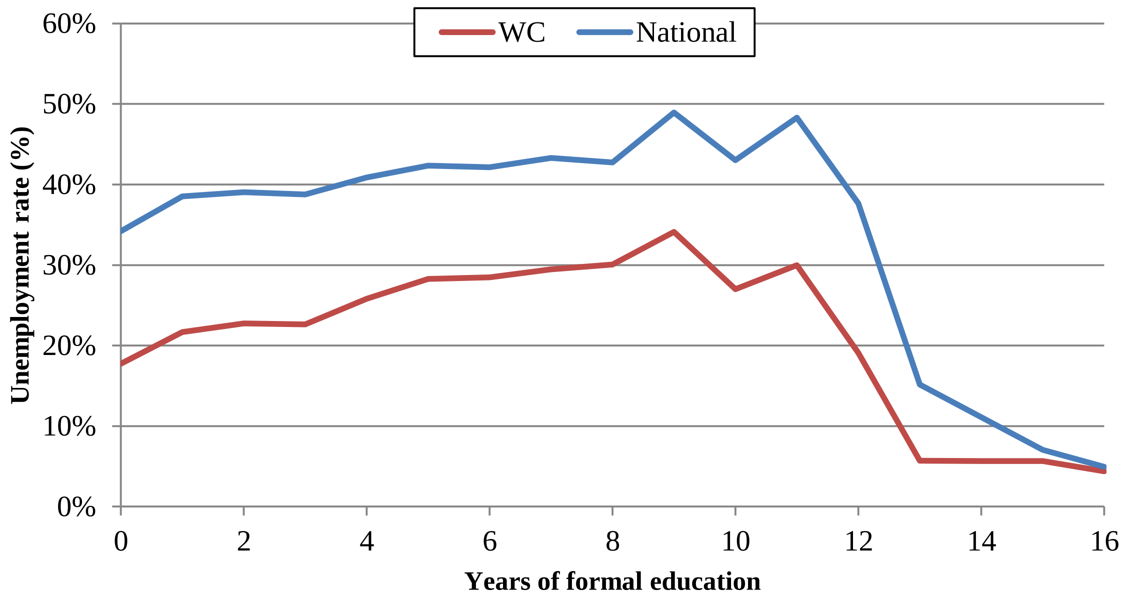

Figure 57: Unemployment rates (1995-2007), by level of education (in years)

Source: Burger (2011)

In a study on the wage dispersion in South Africa, Burger (2010) uses four skills groups, i.e. unskilled, semi-skilled, skilled and highly skilled. Bioenergy systems, however, require some understanding of operations by farm and forest workers, resulting in the combination of unskilled and semi-skilled groups. Based on this, full-time jobs created for each LBS have been subdivided into three income categories (refer also to Table 49, below), namely, number of jobs with an income of less than R8 000/month (direct employment creation potential, DECP I), number of jobs with an income of between R8 000 and R24 000/month (DECP II), and number of jobs with an income greater than R24 000 per month (DECP III). The productivity data applied for each production phase in the multi-period budget models was used to quantify the direct employment potential for each of the categories.

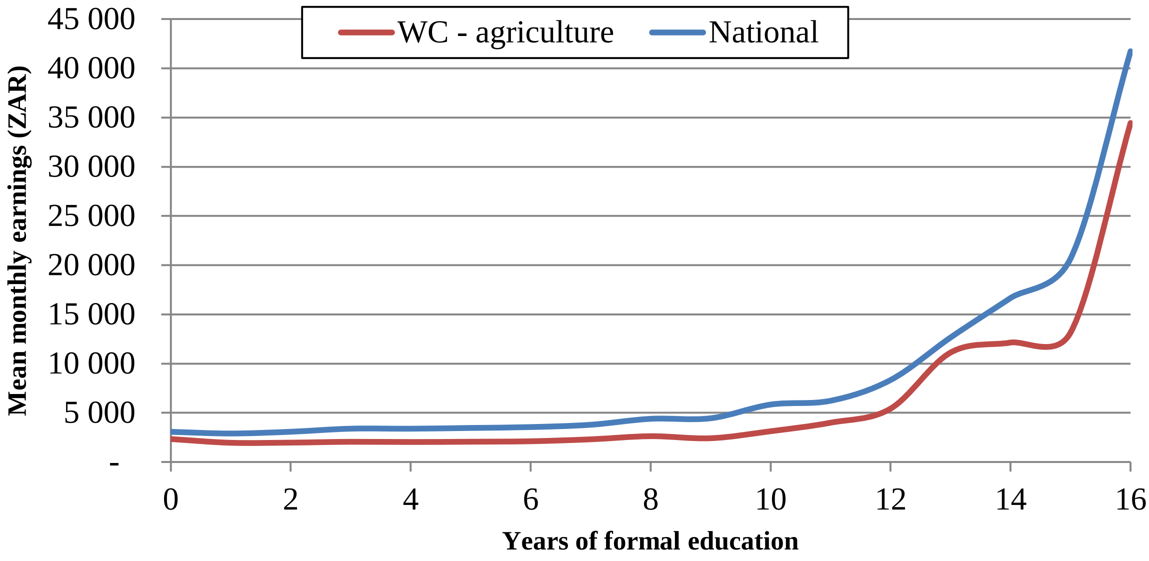

Figure 58: Mean monthly earnings (ZAR) (2003-2007), by level of education (years)

Source: Burger (2011)

Table 49: Bioenergy systems employment creation potential subdivided into income categories

Direct employment creation potential	**Description**	**Income (R/month)**
DECP I (< R8 000/month)	Farm and forest worker	R1 264
	Chainsaw operator	R3 000
	Tractor operator Three-wheeler loader operator	R5 000
	Conversion plant operator	R5 833
	Secondary transport assistant	R6 445
DECP II (R8 000-R24 000/ month)	Combine harvester operator Feller-buncher operator Forwarder-operator	R10 568
	Stationary comminution unit technician	R12 000
	Secondary transport driver	R17 680
DECP III (> R24 000/month)	Stationary comminution engineer	R25 500
	SRC plantation supply chain manager	R29 167
	Conversion plant manager Conversion plant engineer	R33 333

6.4.1.1 DECP I - income less than R8 000 per month

This category comprises the number of jobs created for unskilled to semi-skilled labourers by each LBS, including farm and forest workers, chainsaw, tractor, three-wheeler loader, and conversion plant operators, as well as assistants to truck drivers during secondary transport. The performance in terms of DECP I of each LBS and for each biomass procurement area is illustrated in Figure 59, below. Similar to the LCA impact categories discussed above, the number of jobs created, particularly for this income category, is a function of the overall conversion efficiency of the bioenergy conversion system, the productivity rate of the harvesting system, as well as of the potential biomass losses occurring during harvesting and comminution.

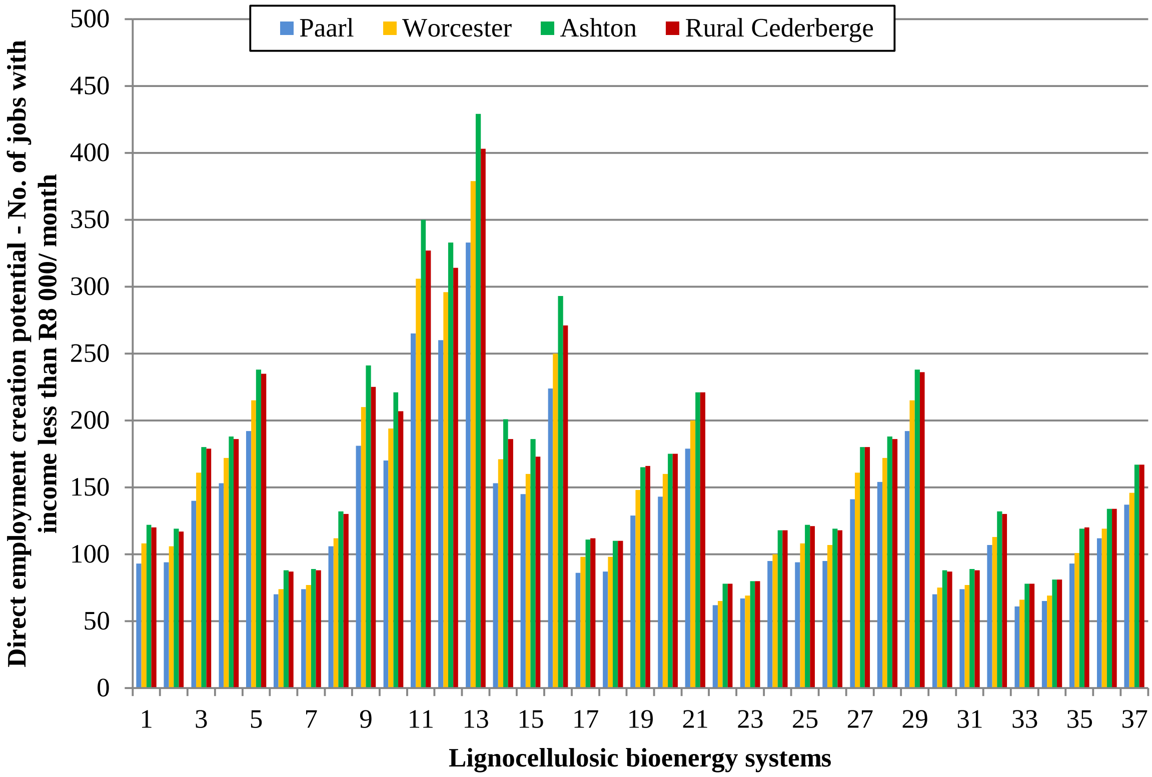

Figure 59: DECP I – No. of jobs with income of less than R8 000/month

For LBS key, refer to Figure 11

Besides employment created directly for the bioenergy conversion systems, all upstream employment creation potential depends on the overall conversion efficiency – the less efficient, the more jobs are created. Hence, LBS 13, with 333, 379, 429 and 403 jobs for BPAs I-IV respectively, is the least favourable in terms of environmental and financial-economic criteria, but is the most favourable in terms of employment potential pertaining to jobs with an income of less than R8 000/month. However, LBS 13 is characterised not only by a relatively low overall conversion efficiency, resulting in greater land requirements and therefore in relatively greater employment force requirements for all upstream activities, but it also uses a relatively inefficient harvesting system, which, together with its labour intensive activities such as the manual loading and unloading of the logs, as well as the manual feeding of the mobile comminution units, contributes to the high number of jobs created in terms of DECP I. Another contributing factor is the high number of mobile fast-pyrolysis units (27), which require at least one skilled operator each per shift.

The least employment creation potential offered in terms of income category I is by LBS 33, with 61, 66, 78 and 78 for BPAs I-IV respectively. This can be explained by the relatively high conversion efficiency of BCS I, resulting not only in relatively less employment created upstream, but also in only three conversion plant operators being required per shift. The LBSs employing BCS II, which is assumed to have the best overall conversion efficiency, require at least seven operators per shift, due to the conversion technology's low degree of automation.

6.4.1.2 DECP II – income from R8 000-R24 000 per month

Direct employment creation potential category II includes all skilled labourers such as operators of combine harvesters, feller-bunchers, forwarders, or service technicians for the stationary comminution units, and truck drivers. Figure 60, below, shows the performance in terms of DECP II for each LBS and biomass procurement area.

For DECP II, the overall conversion efficiency of the bioenergy conversion systems does not play a more significant role than it does for DECP I. The number of truck drivers transporting the bioenergy feedstock from the roadside to a central conversion plant represents the greatest proportion of DECP II. As discussed in section 4.7, the number of trucks, and therefore truck operators, depends, *inter alia*, on the commodity to be transported and the amount thereof, the payload capacity of the truck, the transportation distance, the total transportation time per load and the number of trips per working day completed.

LBSs 9 and 10 yield the lowest employment creation potential for this category, with 3, 2, 2 and 2 for BPAs I-IV respectively, which can be explained by the low biomass demand, due to the relatively high overall conversion efficiencies, but more importantly, by the low level of mechanisation and automation used during the harvesting and forwarding of the biomass feedstock. Only truck operators are required in this category.

The greatest employment creation potential is exhibited by LBS 24 (15, 11, 11, 11 for BPAs I-IV respectively), which is a result of more biomass being required by BCS III, resulting in more biomass having to be transported to the central conversion site, and the use of feller-bunchers and forwarders during harvesting.

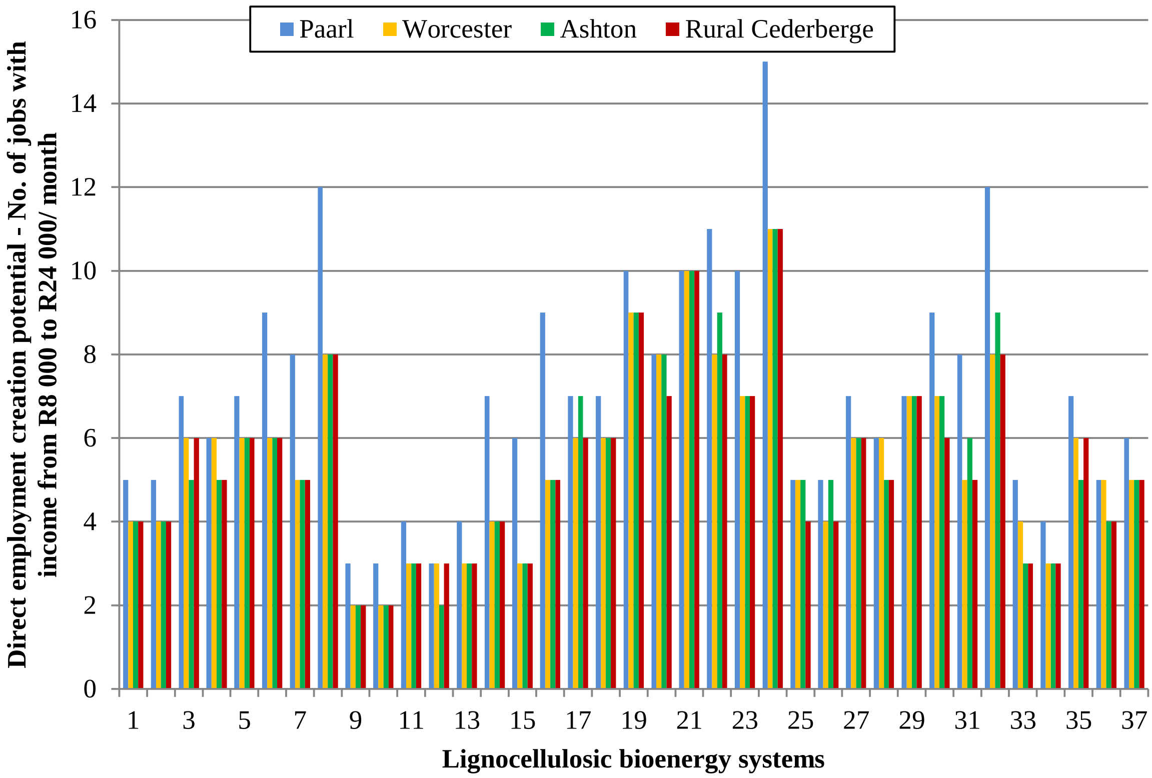

Figure 60: DECP II – no. of jobs with income of between R8 000 and R24 000/month

For LBS key, refer to Figure 11

6.4.1.3 DECP III – income of more than R24 000 per month

Highly skilled labourers having a monthly income of more than R24 000, such as engineers and managers for the conversion plant as well as for the supply chain, are aggregated in the category DECP III. For each LBS, one SRC plantation supply chain manager is included. The LBSs encompassing centralised, stationary comminution require one qualified engineer to supervise the system; the LBSs using BCSs I and II require both one operations manager, as well as one engineer; the LBSs using BCSs III and IV require one manager and two engineers for the upgrading unit and one each for the conversion units. Due to the large number of upgrading units required for the LBSs using BCS V, two unit managers and three engineers are required, with one engineer and one manager being in charge of the conversion unit.

Thus, the LBSs using BCSs I and II, together with mobile comminution, create the least employment in DECP category III. On the other hand, those LBSs that use BCS V as an upgrading and conversion system, create the most employment.

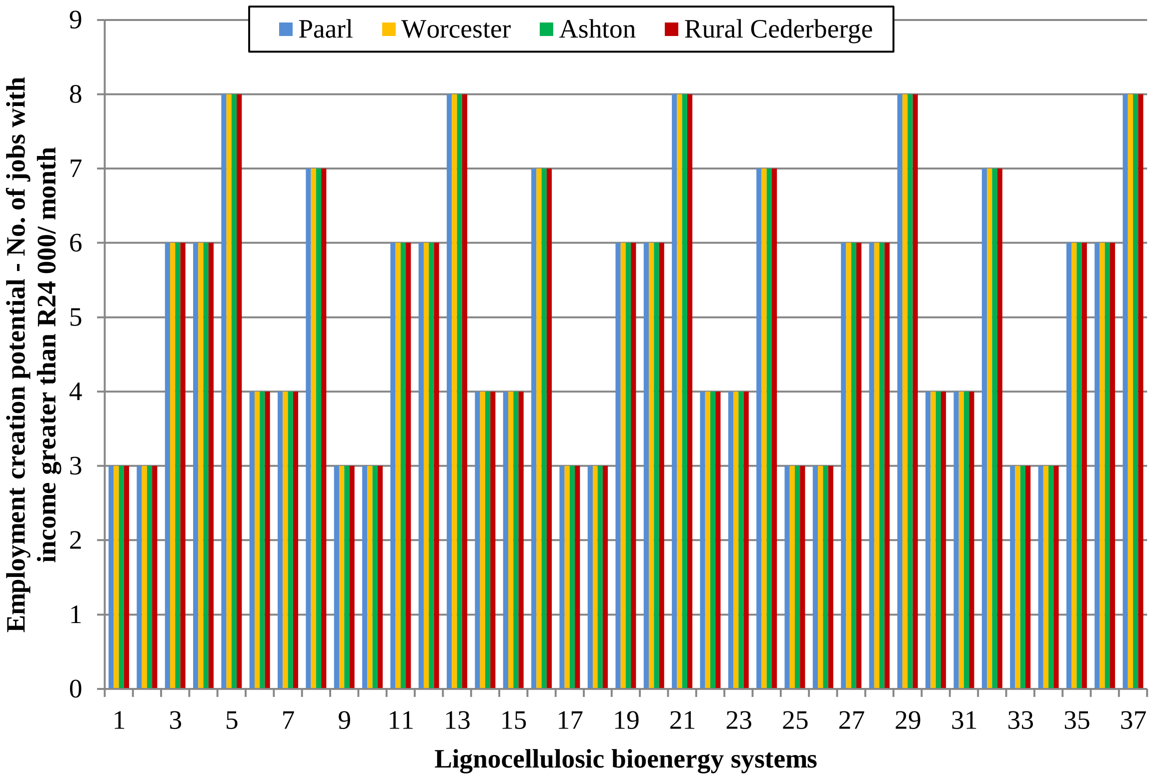

Figure 61: DECP III – No. of jobs with income of more than R24 000/month

For LBS key, refer to Figure 11

6.4.2 Other socio-economic impacts: food security

The competition for land between food, feed and energy production can in some instances lead to a shortage in food supply on a local, regional and national level, affecting, *inter alia*, social cohesion and stability; particularly in the African context, food security plays an important role. However, concerns regarding food security are dealt with in the land availability assessment (Von Doderer, 2009), and by selecting trees as a bioenergy feedstock. Assuming that land will always be used to its highest potential, based on sustainability, and given natural conditions (climate, soil, terrain, among others), trees will only be grown in SRC plantations on marginal and idle land, unlike canola or other bioenergy crops, which compete directly with high-potential food crops.

A potential measure for land use at its highest potential is the land type suitability index value (Naudé et al., 2012), which indicates the soil suitability or potential for annual or perennial crops. However, this index does not reflect the demand side.

6.5 Conclusions

Covered in the LCA framework, this chapter assesses the life-cycle impact of the 37 lignocellulosic bioenergy systems, not only in terms of the LCIA categories, but also in terms of financial-economic viability and socio-economic potential. The results of the life-cycle inventory discussed in Chapter 5 are translated using the 'CML 2001 impact assessment method collection' into environmental impact categories, such as abiotic depletion potential, acidification potential, eutrophication potential, global warming potential, and photochemical ozone creation potential, allowing for a comparison of the LBSs with one another and for a comparison of each biomass procurement area. Furthermore, a general discussion on the environmental impact of the LBSs in terms of biodiversity and water balance is given. The performances of the LBSs in their respective biomass procurement areas are assessed against a set of profitability and cost criteria by means of multi-period budgeting. As a socio-economic indicator, the direct employment creation potential, subdivided into three income categories, is determined by using productivity data for each production phase used in the MPB modelling.

In general, it can be concluded that the main driver for each criterion, whether it be of an environmental, financial-economic or socio-economic nature, is the overall conversion efficiency (OCE) of the biomass upgrading and bioenergy conversion system. The greater the OCE, the less biomass is required, resulting in fewer upstream activities and less land required for biomass production. In terms of the environmental impact of the LBSs, a greater OCE is desired, resulting in lower total emissions and, therefore, in lower impacts for each life-cycle impact category. Similarly, for the financial-economic viability of the LBSs, a greater OCE results in lower costs, both in terms of capital and operating expenditure, as well as in higher internal rates of return on the capital invested. Particularly for biomass procurement area I (Paarl), a lower OCE results in higher biomass and, thus, higher land requirements. This has a negative impact particularly on the profitability of the LBSs, due to the very high land value of BPA I, which is only partially compensated for by its higher biomass productivity. The opposite picture emerges for the socio-economic criteria, expressed in employment creation potential. The lower the OCE, the greater the employment creation potential, particularly for the unskilled and semi-skilled income categories.

Another important driver is the efficiency of the harvesting system, which has an effect similar to the OCE. The greater the degree of mechanisation and automation, the lower the environmental impact and the higher the cost-effectiveness and profitability. LBSs 9 to 16, for instance, comprise motor-manual harvesting with chainsaws, where trees are felled, de-branched and cross-cut to allow for the manual loading of logs, leaving a considerable amount of biomass in the form of branches and tops behind. As only logs are used further on in the process, easing the handling of the biomass, 30 percent of the biomass is left unutilised and, thus, more land needs to be cultivated for SRC plantations, in compensation. The greatest harvesting system efficiency is reached by the modified combine harvester system (LBS 33-37), where felling and comminution occur in a single operation, resulting in a relatively low environmental impact and low production cost, in turn, resulting in a positive impact on overall profitability. However, this harvesting system is also characterised by a relatively low direct employment creation potential.

Table 50, below, shows the best- and worst-performing alternative(s) for each of the environmental, financial-economic and socio-economic criteria discussed in Chapter 6. LBS 34 performs best in terms of most of the environmental and financial-economic criteria, which can be explained by the relatively good OCE and the relatively good harvesting system efficiency. Only in terms of GWP and POCP are other LBSs favoured: LBS 37 for the former criterion, which can be explained by the great carbon storage capacity of biochar, resulting in a negative GWP; and LBS 18 for the latter criterion, which, however, shows only marginally better results than LBS 34.

Table 50: Best- and worst-performing LBSs per selected criteria and BPA

	Best performing LBS [a]				**Worst performing LBS [a]**			
BPA	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**
Environmental criteria								
Abiotic depletion potential	34	34	34	34	16	16	16	16
Acidification potential	34	34	34	34	16	16	16	16
Eutrophication potential	34	34	34	34	16	16	16	16
Global warming potential	37	37	37	37	27	27	27	27
Photochem. ozone creation potential	18	18	18	18	16	16	16	16
Financial-economic criteria								
Internal rate of return	34	34	34	34	11	11	11	11
Capital expenditure – BCS	[b]	[b]	[b]	[b]	[c]	[c]	[c]	[c]
Operational expenditure – BCS	[b]	[b]	[b]	[b]	[d]	[d]	[d]	[d]
Capital expenditure – other	34	34	34	34	13	21	21	21
Operational expenditure – other	34	34	34	34	13	13	13	13
Socio-economic criteria (i.e. direct employment creation potential)								
DECP I (< R8 000/month)	13	13	13	13	33	33	33	33
DECP II (R8 000-R24 000/month)	24	24	24	24	[e]	[e]	[e]	[e]
DECP III (> R24 000/month)	[f]	[f]	[f]	[f]	[g]	[g]	[g]	[g]

Notes:

[a] For LBS key, refer to Figure 11.
[b] LBSs 2, 7, 10, 15, 18, 23, 26, 31 and 34 show the same results.
[c] LBSs 5, 13, 21, 29 and 37 show the same results.
[d] LBSs 4, 12, 20, 28 and 36 show the same results.
[e] LBSs 9 and 10 show the same results.
[f] LBSs 5, 8, 13, 16, 21, 24, 29, 32 and 37 show the same results.
[g] LBSs 1, 2, 9, 10, 17, 18, 25, 26, 33, 34 show the same results.

A different picture is presented for the socio-economic criteria. Here, LBS 13 shows the greatest potential for DECP I and, amongst others, for DECP III. DECP II is led by LBS 24. LBS 13 creates between 333 and 429 jobs with an income of less than R8 000/month for the different biomass procurement areas. In comparison, LBS 34 creates 65 to 81 jobs, only marginally more for this income category than the worst performing LBS. On the other hand, when using IRR as a point of reference, LBS 34 yields between 8.25 and 15.26%. LBS 13, however, gives an IRR of between 1.42 and 3.54%. Thus, only in purely monetary terms would LBS 34 be the obvious choice, resulting in a trade-off in socio-economic terms, as it only reaches a DEPC I of around 20% compared with LBS 13. When comparing LBS 24 and LBS 34 in terms of DEPC II and GWP, another trade-off becomes apparent. While LBS 24 has a DEPC II of 11-15, LBS 34 reaches only between 3 and 4. In contrast, LBS 24 has a GWP of between 864 and 2 768 t CO_2-equivalent, whereas LBS 34 varies between 0 and 958, also showing a trade-off of at least 864 or up to 1 472 t CO_2-equivalent.

The results presented in this chapter set a good example of the complexity of bioenergy systems, constituting a major barrier to the implementation of bioenergy projects, as they are, by definition, embedded in social, economic and environmental contexts and depend on the support of many stakeholders with different points of view. In order to overcome these trade-offs, a tool is required that integrates the various points of view, by helping decision makers to organise and synthesise such information, so that they feel comfortable and confident about making a decision, minimising the potential for post-decision regret by being satisfied that all criteria or factors have properly been taken into account. Multi-criteria decision-making analysis (MCDA) is a tool aimed at aiding such a decision-making process. In the following chapter, the results provided are translated into a common language (scores). During a workshop, experts attached weights to the selected criteria using the commonly accepted and applied analytic hierarchy process (AHP). The combination of the weighted criteria with the scores results in a ranking of the LBSs, with the aim of providing decision support for the CWDM in deciding on what bioenergy system may be the preferred option for implementation.

7 CHAPTER: INTERPRETATION OF LCA RESULTS USING MCDA

7.1 Introduction

The complexity of bioenergy systems constitutes a major barrier to the implementation of bioenergy projects, as they are embedded in economic, social and environmental contexts. Such complexity and the resulting decision-making problem is illustrated by the trade-offs between the defined alternatives presented in the previous chapter, where the performances of 37 lignocellulosic bioenergy systems (LBSs) are compared against a set of 13 key criteria. Overall conversion and harvesting system efficiency are dominating factors contributing to the positive performances of the LBSs in terms of most of the selected economic and environmental criteria. However, besides being concerned about financial-economic profitability and low environmental impact, the public decision makers and other stakeholders may be also interested in improving the socio-economic situation, for instance, by supporting the creation of direct employment. The resultant trade-offs cause a decision-making problem, as those LBSs which do well in terms of the financial-economic and least environmental impact criteria show less favourable performances in terms of the socio-economic criteria.

In this chapter, multi-criteria decision-making analysis (MCDA) is applied with the aim of supporting the public decision makers of the CWDM in their decision-making process. MCDA, which can be defined as a 'formal approach which seeks to take explicit account of multiple criteria in helping individuals and groups explore decisions that matter', stands in contrast to single goal optimisation and approaches using 'unifying units' to offset poor performance in terms of one criterion by good performance in terms of another criterion. This latter approach is adopted in cost-benefit analyses, which use monetary values assigned to parameters, allowing for substitution and comparability between criteria. MCDA with its use of interval scaling and weights and with its focus on relative trade-offs within each dimension avoids many of the problems associated with monetary evaluation techniques, while still permitting the assessment of potential trade-offs between criteria.

Based on the analytic hierarchy process (AHP), one of the commonly applied MCDA approaches, the performances of the LBSs in terms of the selected criteria were translated into a common language (scores). The aggregation of the (unweighted) scores resulted in a ranking of the LBSs, but without taking the conflicting natures of some of the criteria as well as the different viewpoints of potential stakeholders into consideration. With the support of experts, reflecting the various stakeholder perspectives, the relative importance of the selected criteria was determined by attaching weights using the AHP-based Expert-Choice software. In a next step, the weighted criteria were multiplied by the scores of the LBSs and aggregated into a single indicator, resulting in a ranking of the LBSs. This made subjective judgements explicit and transparent, and served as a basis for further discussion, but did not solve the actual decision-making problem for the final decision maker, as trade-offs between the various alternatives could not be resolved.

7.2 The analytic hierarchy process

The MCDA method employed in this study is the analytic hierarchy process (AHP), developed by Saaty (1980). In its execution, it has many similarities with the multi-attribute value theory (MAVT) approach (Belton and Stewart, 2002; Hobbs et al., 1992), both being based on evaluating plausible alternatives in terms of an additive preference function. Although based on different assumptions about value measurement, AHP can be viewed as an alternative means of eliciting a value function. However, it was developed independently of decision theory, and some AHP proponents insist that it is not a value function method at all (Saaty, 1980). Nevertheless, the evidence for the similarity of the AHP and MAVT approaches is the convergence of supporting software, with a number of available packages supporting both eliciting approaches (De Lange, 2010).

As with MAVT, the initial step in AHP is to develop a hierarchy of criteria (criteria value tree) and to identify or develop possible alternatives to be used as inputs. The major factors that differentiate AHP from MAVT are the use of pairwise comparisons of (a) alternatives with respect to criteria and (b) criteria within families, and the use of ratio scales for all judgements. In the standard procedure, alternatives are not differentiated from criteria, but are treated as the bottom level of the hierarchy, and all comparisons follow the same procedure. Rather than constructing a value function or an explicit qualitative scale against which the performances of alternatives are assessed, the decision maker is required to respond to a series of pairwise comparisons, usually using a nine-point scale, which leads to an implied numerical evaluation of the alternatives according to each criterion (Belton and Stewart, 2002: 152). Table 51 shows the fundamental scale for the pairwise comparisons.

Generally, a weighting procedure for the criteria with respect to a goal as well as a scoring procedure of the alternatives with respect to each of the criteria are included in the AHP, which can be made in any order. The scoring procedure is undertaken by means of pairwise comparisons of the alternatives and aims to establish the relative preference order of such alternatives against the goal/objective (Saaty, 2004: 5). Pairwise comparisons of alternatives simply present two alternatives against each other and record the relative preference for one above another in terms of a given criterion on a numerical or semantic scale. In contrast with direct comparison, which compares various alternatives simultaneously (the more alternatives, the more difficult it becomes), pairwise comparison is significantly more simple (Belton and Stewart, 2002: 153). In comparing alternatives with respect to one particular criterion (e.g. implications in terms of financial profitability), participants are requested to express their preferences across alternatives only with respect to that particular criterion (e.g. financial profitability).

Table 51: Fundamental scale for pairwise comparison in AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement slightly favour one criterion over another
5	Essential or strong importance	Experience and judgement strongly favour one criterion over another
7	Very strong importance or demonstrated importance	A criterion is favoured very strongly over another, its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one criterion over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

Source: Saaty (1990: 15)

Once all pairs of alternatives have been compared, the numeric values corresponding to the judgements made are entered into a pairwise comparison matrix, where all diagonal entries are by definition equal to one. The method interprets the strength of preference in terms of a ratio. Thus, if for example, alternative ‘p’ is preferred to alternative ‘q’, with a strength of preference given by ‘S’ $= apq$ (where apg is the entry in the p^{th} row and the q^{th} column of the comparison matrix), then the comparison of q with p is the reciprocal of that value, i.e. $apg = 1/S$ (Belton and Stewart, 2002: 154).

The first step in synthesising the comparison matrix is to reduce it to a comparison vector (a set of scores representing the relative performance of each criterion). The values in the pairwise comparison matrix are interpreted as ratios of underlying scores. Within this context, the aim of the AHP is to find the set of values (weights) that approximates the set of ratios. The standard method for doing this is an eigenvalue analysis of matrices, which is aimed at extracting the eigenvector corresponding to the maximum eigenvalue of the pairwise matrix. This procedure is iterative and not easily performed by hand, but software programs such as Expert Choice extract the relevant values quite easily. The elements of the vector of scores are normalised to sum one (unity), which implies that for each criterion the scores are standardised, such that when a new criterion is added or a current one is deleted from the comparison, the whole structure is changed consistently (Saaty, 2004: 13; De Lange, 2010: 21).

The weighting procedure consists of pairwise comparisons of criteria to elicit the relative preferences of decision makers. This step compares all criteria within each criteria group, using the same pairwise comparison procedure described above to derive the vector indicating the contribution of the criteria relative to the group of criteria. Respondents are asked questions similar to the procedure described above, but now compare criteria against each other within the same group. The weighting is done on the same numerical or semantic scale as for the scoring procedure. The preferences are again aggregated by working upwards from the bottom of the hierarchy (bottom-up approach).

These weights are then multiplied by the relative performance (score) of each alternative against the said criteria, to present a weighted score for the particular criteria (Saaty, 2004: 13). The aggregated final score of all criteria for each alternative facilitates a ranking of alternatives, which feeds directly into the decision-making process. Worth noting is that the preference ordering should be done with a set goals/objectives in mind. The strength of the approach depends on the way it is used to facilitate understanding, learning and discussion, which in turn depends on the interaction of the participants and the effectiveness of displaying the information to participants (De Lange, 2010: 22).

Sensitivity analysis may then be used to investigate the significance of missing information, to explore the effect of decision makers' uncertainty about their values and priorities, or to offer a different perspective on the problem. However, there may be no practical or psychological motivation for changing values; the exploration may be driven simply by a wish to test the robustness of the results. Nonetheless, Saaty (1996) developed a consistency index that compares the scores/weights with a value derived by generating random reciprocal matrices of the same size, to give a consistency ratio which is meant to have the same interpretation no matter what the size of the matrix. A consistency ratio of 0.1 or less is generally seen as acceptable (Saaty, 2004: 9).

It is clear from the algebraic structure of the additive model used both in MAVT and AHP that the weight parameters define the desirable levels of trade-offs between performances in terms of the different criteria when measures of performances are given in scores. Because of the scaling of the partial scores to sum unity, the implied meaning of 'weight' in the standard AHP procedure is the relative value of the total (or average) score for different criteria – thus it can only be defined by all the alternatives under consideration, which is much more complex to conceptualise. It is not at all evident that decision makers have this interpretation in mind when they express relative weight ratios. In addition, AHP assumes that all comparisons can be made on a ratio scale, which implies the existence of a natural reference point. This makes sense for comparisons of distance or area or monetary units, but it does not make sense for qualitative comparisons such as for comfort, image or quality of life, for which no clear reference level exists. Kahneman and Tversky (1979, 1981) have illustrated that reference points are strongly influenced by the framing of problems, while the framing will almost inevitably change from one pairwise comparison to another, so that in general, stable reference points cannot be expected to occur (Kahneman and Tversky, 1979; Tversky and Kahneman, 1981; Kahneman, 2003).

A number of reasons have led to the popularity of AHP, despite the criticisms mentioned above: psychological research shows that the human brain can consider only a limited amount of information, so all factors cannot be resolved in one's head (Belton and Stewart, 2002: 2). Experience and other anecdotal evidence suggests (Belton and Stewart, 2002: 114) that decision makers are quite happy to express their opinions regarding relative importance in ratio terms, e.g. the one criterion being more important than the other. AHP makes direct use of such intuitive statements, by allowing decision makers to give verbal descriptions of relative importance in terms such as 'moderately', 'strongly' or 'absolutely' more important, which are converted into assumed ratios. The natural appeal of such semantic scales for expressing relative importance explains, *inter alia*, the popularity of AHP.

However, this study employed only parts of the MCDA procedure, requiring judgements only for the weighing of the defined set of criteria in order to overcome the trade-offs between the LBSs indicated in section 6.5. The performances of the LBSs were determined in terms of quantitative measures using standardised, quantitative assessment methods, where natural reference points existed. Thus, the performances were based on sound, objective data, rather than on subjective judgements by decision makers or 'objective' experts, who often rely on their 'gut-feel'.

7.3 Problem identification and structuring

The first MCDA phase, problem identification and structuring, is covered in the LCA part of this study, where the goal is defined as "supporting the public decision maker in determining the best-suited or 'optimal' bioenergy system for the CWDM". The alternatives are defined in Chapter 4, 'Goal and scope definition' (refer also to Figure 11); their features and key issues are discussed in Chapter 5, 'Life-cycle inventory', while Chapter 6 presents the life-cycle impact assessment, where the LBSs are assessed against a set of predefined criteria.

7.4 Model building and use

As mentioned in section 3.3.2, during the second phase (model building and use) of a conventional MCDA, after extracting the essence of the decision problem, the decision maker's preferences, value trade-offs, goals and objectives, and other requirements are translated by developing a formal model so that the alternatives under consideration can be compared relative to one another in a systematic and transparent manner.

7.4.1 Criteria value tree

The initial step during the second phase of an MCDA is to develop a hierarchy of criteria (criteria value tree), which consists of a goal, at which the decision making process is aimed; main criteria, which describe relatively broad general interests (e.g. social, economic and environmental concerns); and various levels of sub-criteria, which are more specific (e.g. IRR, GWP). Figure 62 shows the proposed hierarchical value tree for the CWDM's decision-making problem concerning the choice of bioenergy system, based on the criteria applied in Chapter 6.

The goal was defined, as 'Identifying the most viable/sustainable for the CWDM'. The main criteria were based on the 'three-legged stool' of sustainability (Brady, 2005: 33), i.e. (i) financial-economic viability, (ii) socio-economic potential (i.e. direct employment creation potential), and (iii) least environmental impact. The sub-criteria, which are based on the criteria defined in Chapter 6, were grouped accordingly. The financial-economic viability criterion was divided into three sub-criteria, namely internal rate of return, cost of conversion system, and cost other than conversion system. The latter two were further subdivided into capital expenditure and operational expenditure. The socio-economic potential criterion encompasses three sub-criteria, i.e. direct employment creation potential I (DECP I: number of jobs providing a monthly income of less than R8 000), DECP II (number of jobs providing an income of R8 000-R24 000/month), and DECP III (number of jobs providing an income of more than R24 000/month). The last main criterion, 'Least environmental impact', consists of two sub-criteria, namely 'Least local impact' and 'Least global impact'. The latter consists of another two sub-criteria, i.e. 'Lowest abiotic depletion potential' (ADP) and 'Lowest global warming potential' (GWP), while 'Lowest local environmental impact' was subdivided into 'Lowest acidification potential' (AP), 'Lowest eutrophication potential' (EP) and 'Lowest photochemical ozone creation potential' (POCP).

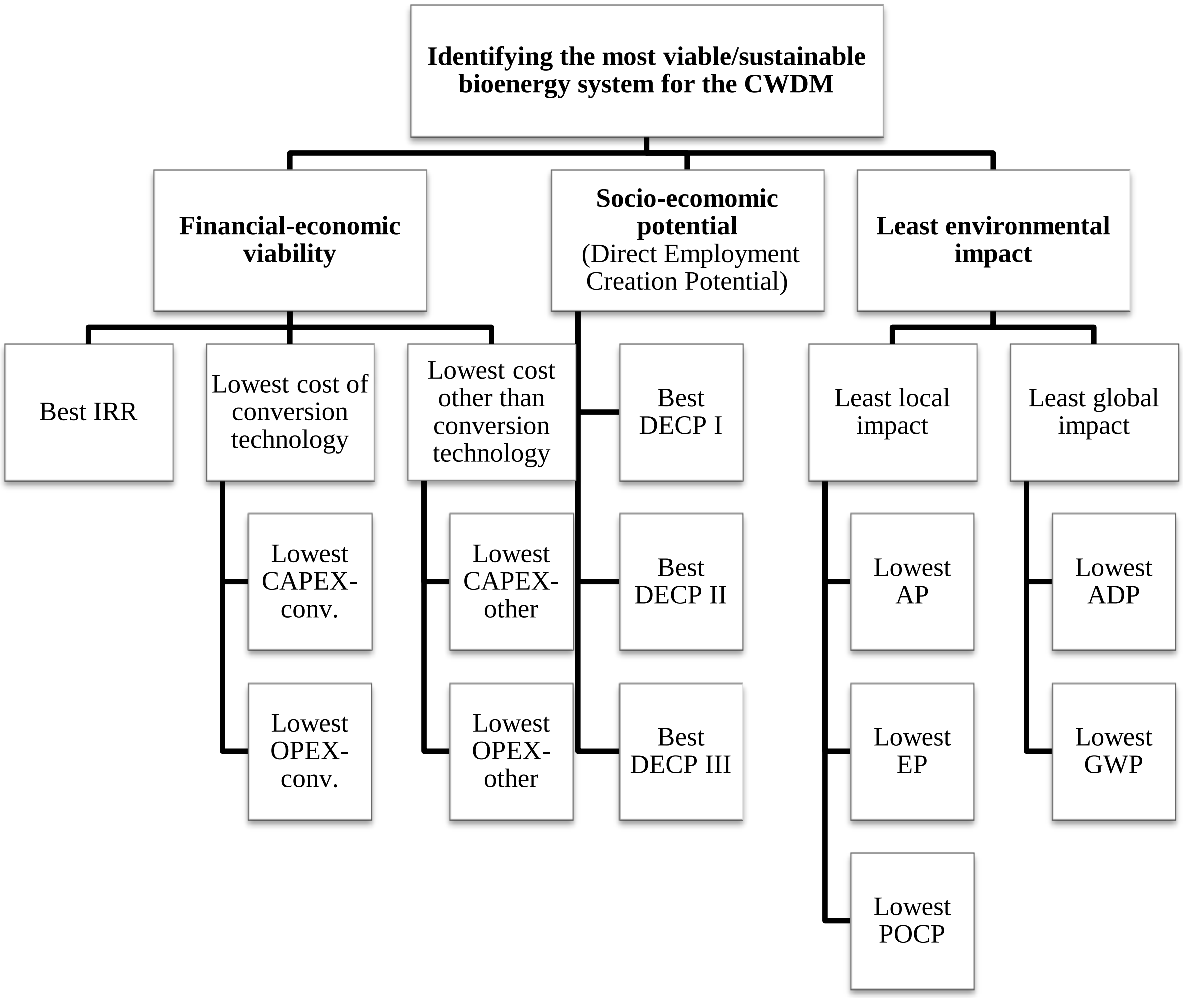

Figure 62: Hierarchical value tree for the CWDM's decision-making problem concerning choice of bioenergy system

Notes:

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operating expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operating expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential – income of less than R8 000/month
DECP II	Direct employment creation potential – income of R8 000-R24 000/month
DECP III	Direct employment creation potential – income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

7.4.2 Normalisation of LCA results

In order to create consistency among the results, the absolute numeric values corresponding to the LBSs need to be translated into an interval scale of measurement (scores), i.e. a scale on which the difference between points is the important factor. Thus, to construct a scale, it is necessary to define two reference points and to allocate numerical values, e.g. 0-100, to these points.

For the translation into standardised scores, the local scaling approach was selected, where the local scale is defined by the set of alternatives under consideration, i.e. the performances of the alternatives for a particular criterion are normalised to sum one. The alternative that does best on a particular criterion exhibits the greatest score, while the one that does the worst is represented by the lowest score. All other alternatives receive intermediate scores that reflect their performances proportionally. The local scaling method is preferred, since it is easy to implement, and since the set of alternatives allows for the consistent assessment of each of the selected criteria. Another approach, the 'global scaling approach', is defined in reference to a wider set of possibilities, where the end points are defined by the ideal and the worst conceivable performances that could realistically occur. The latter approach however, requires more work than would be required on a local scale, and the definitions of the end points may be debatable in terms of what performances can realistically occur. One form of global scaling is the 'distance-to-target scoring approach', where impact categories are evaluated according to the distance between the current level and a future target value (Seppälä and Hämäläinen, 2001).

Furthermore, to determine the ratio scale, consideration must be given to the direction of the original scale, which can be

- **Monotonically increasing** against the natural scale, i.e. the highest value is the most preferred, and the lowest is least the preferred, or vice versa;
- **Monotonically decreasing** against the natural scale; and
- **Non-monotonic**, i.e. an intermediate point on the scale defines the most preferred or least preferred point (often an indication that the proposed measure actually reflects two conflicting values).

The directions of the original natural scales of the criteria applied in this study are either monotonically increasing or decreasing. However, to simplify interpretation of the scores, all local scales were converted to a monotonically increasing direction, i.e. the highest value is the most preferred, and the lowest is the least preferred.

The original values for the sub-criterion 'Internal rate of return on capital investment' were expressed as a percentage and represent a measure of performance in terms of profitability (refer to section 5.3.1). Thus, the greater the IRR, the better the profitability of a particular alternative, indicating a monotonically increasing direction. The other financial-economic sub-criteria 'Cost of conversion technology' and 'Cost other than conversion technology' were each further subdivided into 'Capital expenditure' and 'Operational expenditure', and were expressed in monetary terms representing the risk associated with the investment (refer to sections 5.3.2-5.3.3). The direction of the natural scale for these criteria is monotonically decreasing, i.e. the higher the cost, the less favourable it is as an alternative. However, during the normalisation process, the reciprocal value was used, resulting in ratio scales with monotonically increasing directions, i.e. the lower the respective cost for a particular alternative, the greater the score on the ratio scale (i.e. more favourable), and the higher the cost, the lower the score. Similar to the IRR, sub-criteria DECP I-III are also all moving in a monotonically increasing direction, i.e. the more employment is created, the more favourable the particular alternative is and the greater the score.

The original results for the environmental impact criteria are monotonically decreasing, i.e. the lower the particular impact, the more preferable a particular alternative. Thus, similar to the cost-related criteria, by using the reciprocal values, the resulting ratio scales increase monotonically, favouring those alternatives with the least environmental impact. Table 52 shows the normalised, but unweighted performances/scores of the LBSs for biomass procurement area (BPA) I (refer also to Annexures 53-60).

Figure 63, below, shows the normalised (to sum one) and aggregated, but unweighted scores for the set of 37 LBSs for biomass procurement area I. The ratio scale sums 100 and is subdivided into percentages according to the weighted scores of the LBSs. With a share of 3.76 percent, LBS 37 attains the highest aggregated, unweighted score, followed by LBS 29 (3.73%) and LBS 21 (3.71%), while LBSs 3, 12 and 11 show the weakest performances with 1.97, 1.87 and 1.84 percent respectively.

Around 60% of LBS 37's performance can be explained by its relatively low environmental impact (refer to green colour shades). Similar profiles are shared by top-ranked LBSs 5, 13, 21 and 29, which employ – along with LBS 37 – the same biomass upgrading and conversion technology. All of them use only bio-oil to generate electricity, while the by-product bio-char is used as a soil additive, which effectively acts as a carbon sink. This effect is covered by the 'Least global warming potential' criterion and contributes around one third of the aggregated unweighted score of the top-five-ranked LBSs. In comparison, the GWP score for LBS 23, which is ranked sixth in BPA I, is around 32 times lower than that of top-ranked LBS 37. Another major factor contributing to the overall performance of the top-five-ranked LBSs is their DECP III, with a relative share of 13-15 percent.

Table 52: Normalised to sum one, but unweighted scores for BPA I

LBS	**Financial-economic criteria**					**Socio-economic criteria**			**Environmental impact criteria**					**Sum**
	IRR (25 years)	Cost of conversion technology		Cost other than conversion technology		Direct employment creation potential			Local impact			Global impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (25 yrs)	OPEX (25 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	0.35%	0.31%	0.31%	0.23%	0.24%	0.09%	0.10%	0.00%	0.26%	0.18%	0.25%	0.25%	0.05%	2.63%
2	0.37%	0.40%	0.42%	0.29%	0.27%	0.10%	0.10%	0.00%	0.36%	0.12%	0.30%	0.27%	0.05%	3.05%
3	0.00%	0.13%	0.10%	0.11%	0.18%	0.23%	0.20%	0.29%	0.05%	0.31%	0.11%	0.19%	0.05%	1.97%
4	0.11%	0.01%	0.00%	0.16%	0.23%	0.27%	0.15%	0.29%	0.13%	0.26%	0.15%	0.25%	0.07%	2.09%
5	0.16%	0.00%	0.05%	0.04%	0.15%	0.38%	0.20%	0.49%	0.28%	0.17%	0.22%	0.20%	1.27%	3.60%
6	0.36%	0.31%	0.31%	0.25%	0.24%	0.03%	0.31%	0.10%	0.24%	0.18%	0.24%	0.21%	0.06%	2.83%
7	0.37%	0.40%	0.42%	0.30%	0.28%	0.04%	0.25%	0.10%	0.34%	0.12%	0.29%	0.24%	0.06%	3.20%
8	0.01%	0.13%	0.10%	0.16%	0.19%	0.13%	0.46%	0.39%	0.01%	0.31%	0.09%	0.13%	0.07%	2.19%
9	0.25%	0.31%	0.31%	0.17%	0.13%	0.35%	0.00%	0.00%	0.26%	0.18%	0.18%	0.17%	0.06%	2.37%
10	0.25%	0.40%	0.42%	0.25%	0.18%	0.32%	0.00%	0.00%	0.35%	0.12%	0.24%	0.20%	0.06%	2.79%
11	0.00%	0.13%	0.10%	0.11%	0.06%	0.59%	0.05%	0.29%	0.04%	0.32%	0.01%	0.07%	0.06%	1.84%
12	0.04%	0.01%	0.00%	0.15%	0.12%	0.58%	0.00%	0.29%	0.12%	0.27%	0.07%	0.14%	0.07%	1.87%
13	0.08%	0.00%	0.05%	0.00%	0.00%	0.79%	0.05%	0.49%	0.27%	0.17%	0.11%	0.06%	1.27%	3.35%
14	0.27%	0.31%	0.31%	0.22%	0.17%	0.27%	0.20%	0.10%	0.23%	0.18%	0.17%	0.12%	0.06%	2.61%
15	0.27%	0.40%	0.42%	0.27%	0.22%	0.24%	0.15%	0.10%	0.33%	0.12%	0.23%	0.16%	0.06%	2.97%
16	0.00%	0.13%	0.10%	0.13%	0.11%	0.48%	0.31%	0.39%	0.00%	0.32%	0.00%	0.00%	0.07%	2.04%
17	0.35%	0.31%	0.31%	0.21%	0.24%	0.07%	0.20%	0.00%	0.26%	0.18%	0.28%	0.27%	0.02%	2.71%
18	0.36%	0.40%	0.42%	0.27%	0.27%	0.08%	0.20%	0.00%	0.36%	0.12%	0.32%	0.29%	0.03%	3.12%
19	0.00%	0.13%	0.10%	0.08%	0.18%	0.20%	0.36%	0.29%	0.05%	0.31%	0.15%	0.22%	0.01%	2.09%
20	0.10%	0.01%	0.00%	0.14%	0.23%	0.24%	0.25%	0.29%	0.13%	0.26%	0.19%	0.27%	0.03%	2.16%
21	0.15%	0.00%	0.05%	0.01%	0.15%	0.34%	0.36%	0.49%	0.28%	0.17%	0.27%	0.23%	1.22%	3.71%
22	0.35%	0.31%	0.31%	0.23%	0.23%	0.00%	0.41%	0.10%	0.24%	0.18%	0.27%	0.23%	0.03%	2.90%
23	0.37%	0.40%	0.42%	0.28%	0.27%	0.02%	0.36%	0.10%	0.34%	0.12%	0.32%	0.25%	0.04%	3.27%
24	0.00%	0.13%	0.10%	0.12%	0.19%	0.10%	0.61%	0.39%	0.01%	0.31%	0.14%	0.16%	0.03%	2.29%
25	0.38%	0.31%	0.31%	0.27%	0.25%	0.10%	0.10%	0.00%	0.26%	0.18%	0.27%	0.25%	0.01%	2.71%
26	0.39%	0.40%	0.42%	0.32%	0.29%	0.10%	0.10%	0.00%	0.36%	0.12%	0.32%	0.28%	0.02%	3.12%
27	0.04%	0.13%	0.10%	0.20%	0.20%	0.23%	0.20%	0.29%	0.04%	0.32%	0.14%	0.19%	0.00%	2.10%
28	0.13%	0.01%	0.00%	0.25%	0.25%	0.27%	0.15%	0.29%	0.12%	0.27%	0.19%	0.25%	0.02%	2.20%
29	0.19%	0.00%	0.05%	0.13%	0.17%	0.38%	0.20%	0.49%	0.28%	0.17%	0.26%	0.20%	1.21%	3.73%
30	0.38%	0.31%	0.31%	0.30%	0.25%	0.03%	0.31%	0.10%	0.23%	0.18%	0.26%	0.21%	0.03%	2.90%
31	0.40%	0.40%	0.42%	0.33%	0.29%	0.04%	0.25%	0.10%	0.33%	0.12%	0.31%	0.24%	0.03%	3.26%
32	0.05%	0.13%	0.10%	0.23%	0.21%	0.13%	0.46%	0.39%	0.00%	0.32%	0.13%	0.13%	0.02%	2.30%
33	0.38%	0.31%	0.31%	0.33%	0.27%	0.00%	0.10%	0.00%	0.27%	0.18%	0.27%	0.28%	0.06%	2.76%
34	0.40%	0.40%	0.42%	0.37%	0.30%	0.01%	0.05%	0.00%	0.36%	0.12%	0.32%	0.30%	0.06%	3.11%
35	0.05%	0.13%	0.10%	0.28%	0.22%	0.09%	0.20%	0.29%	0.06%	0.31%	0.15%	0.24%	0.06%	2.18%
36	0.14%	0.01%	0.00%	0.30%	0.26%	0.15%	0.10%	0.29%	0.13%	0.26%	0.19%	0.30%	0.08%	2.22%
37	0.19%	0.00%	0.05%	0.20%	0.19%	0.22%	0.15%	0.49%	0.29%	0.16%	0.27%	0.26%	1.28%	3.76%
Sum:	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	100.00%

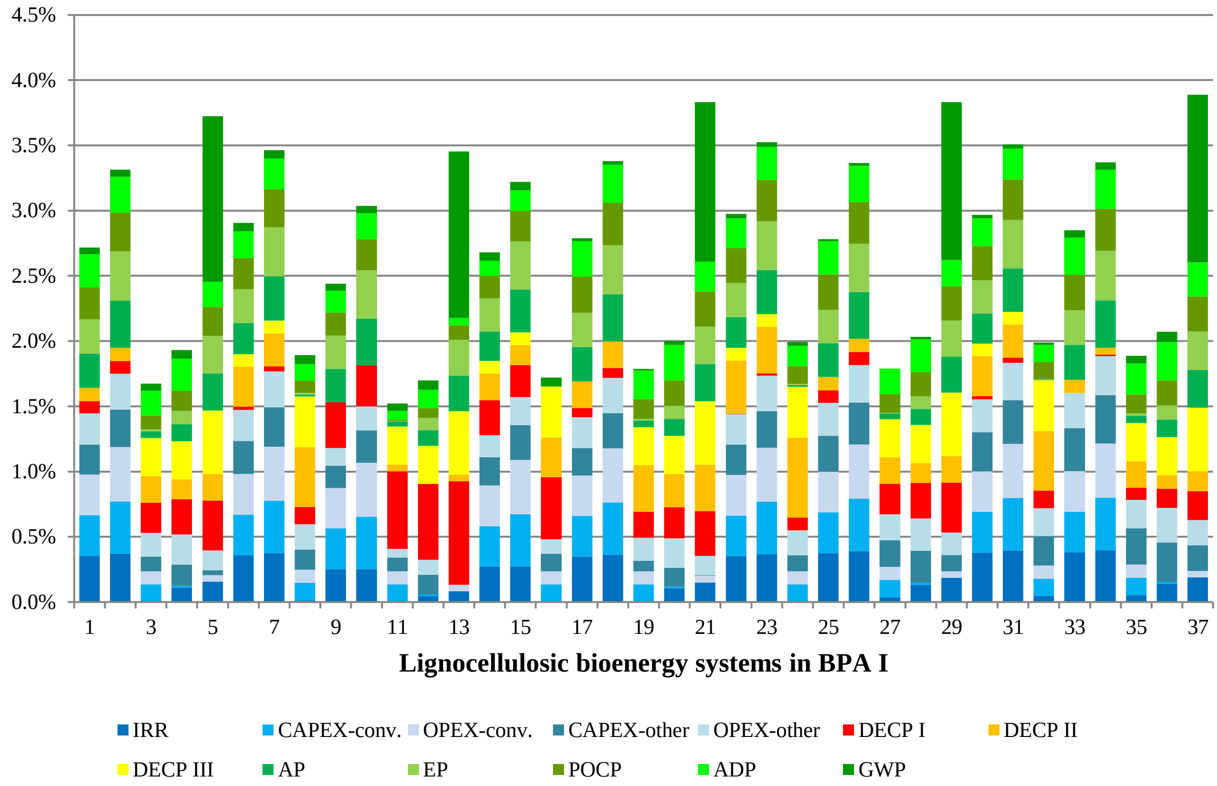

Figure 63: Aggregated, unweighted scores of LBSs for BPA I

For LBS key, refer to Figure 11

Notes:

IRR	Internal rate of return on capital invested
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

As mentioned above, the first LBS not employing bioenergy conversion system (BCS) V is sixth-ranked LBS 23, which is characterised by its relatively strong financial-economic performance, contributing more than 50 percent to its overall performance, while almost 15% of its overall performance is contributed by the socio-economic potential criteria, and the remainder by the environmental impact criteria. Nearly 50 percent of the aggregated scores of bottom-ranked LBSs 11 and 12 are accounted for by the socio-economic criteria, followed by around 30 percent for the environmental impact criteria and around 20 percent for the financial-economic criteria.

Table 53: Ranking of LBSs based on unweighted scores

Ranking	BPA I		BPA II		BPA III		BPA IV	
	LBS	AUS	LBS	AUS	LBS	AUS	LBS	AUS
1	37	3.889%	37	3.850%	37	3.854%	29	3.955%
2	21	3.833%	29	3.818%	21	3.823%	37	3.953%
3	29	3.831%	21	3.814%	29	3.819%	21	3.948%
4	5	3.724%	5	3.655%	5	3.647%	5	3.737%
5	23	3.525%	13	3.512%	13	3.461%	13	3.588%
6	31	3.507%	23	3.362%	31	3.377%	23	3.363%
7	7	3.463%	31	3.339%	23	3.350%	31	3.331%
8	13	3.453%	18	3.330%	26	3.317%	18	3.310%
9	18	3.381%	34	3.330%	34	3.302%	34	3.298%
10	34	3.370%	26	3.309%	18	3.291%	26	3.278%
11	26	3.365%	7	3.289%	7	3.284%	7	3.268%
12	2	3.313%	2	3.255%	2	3.224%	2	3.214%
13	15	3.220%	15	3.133%	15	3.104%	15	3.101%
14	10	3.037%	10	3.077%	30	3.033%	10	3.040%
15	22	2.975%	30	2.875%	10	3.026%	22	2.852%
16	30	2.967%	33	2.837%	22	2.910%	30	2.837%
17	6	2.906%	22	2.823%	17	2.794%	33	2.764%
18	33	2.850%	25	2.785%	6	2.782%	6	2.756%
19	17	2.788%	6	2.764%	25	2.778%	17	2.752%
20	25	2.780%	17	2.733%	33	2.774%	25	2.737%
21	1	2.717%	1	2.676%	1	2.668%	1	2.653%
22	14	2.680%	14	2.628%	14	2.613%	14	2.617%
23	9	2.441%	9	2.520%	9	2.482%	9	2.498%
24	36	2.071%	36	2.203%	36	2.162%	36	2.157%
25	28	2.032%	28	2.138%	20	2.120%	28	2.099%
26	20	2.000%	20	2.098%	28	2.094%	35	2.072%
27	24	1.992%	35	2.059%	32	2.080%	20	2.055%
28	32	1.987%	4	2.041%	35	2.044%	24	2.017%
29	4	1.932%	24	1.987%	24	2.037%	32	2.007%
30	8	1.893%	32	1.978%	4	1.993%	4	1.974%
31	35	1.887%	27	1.926%	27	1.960%	27	1.942%
32	27	1.789%	12	1.903%	19	1.942%	19	1.910%
33	19	1.787%	19	1.902%	8	1.913%	12	1.896%
34	16	1.721%	8	1.873%	12	1.822%	8	1.873%
35	12	1.698%	3	1.790%	3	1.761%	3	1.770%
36	3	1.673%	16	1.739%	16	1.727%	16	1.732%
37	11	1.523%	11	1.652%	11	1.631%	11	1.647%

Notes:
LBS Lignocellulosic bioenergy system
BPA Biomass procurement area
AUS Aggregated unweighted scores
For LBS key, refer to Figure 11

The ranking of the LBSs in terms of normalised, but unweighted scores for each biomass procurement area is presented in Table 53. For all of the biomass procurement areas, LBSs 5, 13, 21, 29 and 37 are among the top-six-performing alternatives, exhibiting similar performances/score profiles to BPA I. In comparison, the other LBSs exhibit similar performance profiles for BPAs II-IV, as illustrated by similar patterns which can be found in Annexure 62-64, while the related data for the unweighted scores of the LBSs is presented in Annexure 59-61.

7.4.3 Discussion on thresholds

In MCDA, thresholds often play an important role in assessing the performances of alternatives, using quantitative data. They can give ranges for which alternatives are perceived to be the same (indifference thresholds) or for which alternatives definitively outrank each other (preference thresholds – refer in this regard to Mendoza and Martins (2006: 12)). However, while thresholds are appealing due to their intuitive logic, precise thresholds often do not reflect the whole 'truth' of a complex system, given that they attempt to quantify what are often 'fuzzy' perceptions on the part of the human decision makers involved, and therefore, they might create false certainties. The legitimacy of thresholds also depends on who sets them in first place.

Thresholds can also be applied to eliminate the risk of the absolute substitution of one criterion with another. For instance, an alternative may outrank all the other competing ones because it is by far the most cost-efficient, but at the same time, it may create prohibitively large negative impacts on the environment. Thus, thresholds could be used to render alternatives invalid once a threshold for one criterion is violated (Buchholz et al., 2009: 490).

In this study, for instance, by assuming the prerequisite of profitability, a threshold could be an IRR of greater than zero. Some of the LBSs exhibit IRRs of less than zero (refer to Figure 51 or Annexure 45), indicating non-profitability. These LBSs would have been excluded if IRR thresholds of greater than zero had been applied. However, they do show relatively high direct employment creation potentials (refer to section 5.4.1), resulting in a trade-off between IRR and DECP. While a private investor may be particularly interested in the profitability of the project, a public investor may be more interested in employment creation and may be willing to compensate for the resulting opportunity cost. Thus, no thresholds are applied in this study.

7.4.4 Expert panel workshop

With the LCA results normalised into scores, the following step deals with the weighing of the criteria to elicit the relative preferences of the decision makers. In this study, a group of experts from various backgrounds was tasked with attaching weights to the predefined criteria during a workshop aimed at supporting the public decision makers in the CWDM. The workshop was held at the Department of Agricultural Economics at Stellenbosch University on 1 September 2011. Aimed at attaining a somewhat representative mix in terms of the selected criteria, the task group assembled members of the CWDM and representatives from the Department of Agriculture of the Western Cape, the banking sector, the farming community, environmental protection institutions, and resource and energy experts. A list of the names and respective backgrounds of the participants is given in Annexure 65.

After familiarising participants with the background and aim of the study, the expert panel was introduced to the set of LBSs, their components, and the predefined criteria. Further, the original results, as well as the unweighted scores/performances of the LBSs for each of the biomass procurement areas (described in the previous section) were presented to the expert panel, serving as a starting point for the 'plenary session', where discussion and assessment of the various alternatives led to – after consensus had been reached – the weighting of the criteria, resulting in a ranking of the LBSs in a consistent and transparent manner. The AHP-based Expert Choice software was used to establish the relative preferences in terms of pairwise comparisons, using a semantic scale for the weighting procedure (refer to Table 51).

Prior to the workshop, the hierarchy value tree and the unweighted LBS scores were loaded into the Expert Choice software, allowing the LBSs to be ranked – viewable in simple static visual displays – immediately after the weighting procedure had been completed. This provided a powerful vehicle for reflecting back to the decision makers the information they had provided, the judgements they had made, and an initial attempt at synthesising these, giving direct feedback and testing of the decision makers' judgements.

7.4.5 Expert panel workshop – outcome

The assessment was conducted using the bottom-up approach, i.e. by assessing the relative weights within each criteria group to derive the vector indicating the contribution of the criterion relative to the group of criteria, which was then aggregated to the higher level. No serious conflicts in opinion between the participants were recorded during the discussions and the weighting procedure, resulting in consensus on a set of weights, which is presented in Table 54, below. Relative weights are assessed within families of criteria, i.e. the weights of criteria sharing the same parent are aggregated and normalised to sum 100. The cumulative weight of a criterion is the product of its relative weight compared with its siblings and the relative weight of its parent, parent's parent, and so on to the top of the tree. The cumulative weights of all bottom-level criteria, by definition, sum

100. The cumulative weight of a parent criterion is the total of the cumulative weights of its descendents.

Table 54: Outcome of weighting procedure

Goal	Main criteria	RW (%)	Sub-criteria – level 1	RW (%)	Sub-criteria – level 2	RW (%)	*CW (%)*
Identifying the most viable/ sustainable for the CWDM	Financial-economic viability	59.36	Best IRR	72.48	-	-	*43.03*
			Lowest cost of conversion technology	15.04	Lowest CAPEX-conv.	75.00	*6.70*
					Lowest OPEX-conv.	25.00	*2.23*
			Lowest cost other than conversion technology	12.48	Lowest CAPEX-other	16.67	*1.24*
					Lowest OPEX-other	83.33	*6.17*
	Socio-economic potential	24.93	Best DECP I	73.06	-	-	*18.22*
			Best DECP II	18.84	-	-	*4.50*
			Best DECP III	8.10	-	-	*2.02*
	Environ-mental impact	15.71	Least local impact	83.33	Least AP	25.83	*3.38*
					Least EP	63.70	*8.34*
					Least POCP	10.47	*1.37*
			Least global impact	16.67	Least ADP	85.71	*2.24*
					Least GWP	14.29	*0.37*

Notes:

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential
CW	Cumulative weight expressed in percent
RW	Relative weight expressed in percent

In terms of the findings of the expert group, the most important main criterion is ‘Financial-economic viability’, representing almost 60 percent in relative weight – more than twice as much as the second-ranked main criterion ‘Socio-economic impact’ (25%) and nearly four times as much as the third-ranked main criterion ‘Least environmental impact’ (16%). ‘Best internal rate of return on capital investment’ is the single most important sub-criterion with a cumulative weight of 43 percent. The experts justified this with the prerequisite of financial viability, i.e. if the LBS was not profitable, private investors would not be interested in investing in this particular alternative. However, it was also noted that from a private investor's perspective, LBSs that are characterised by greater socio-economic potential but are less profitable could also be considered if private investors were compensated for their loss in profitability, in order to support socio-economic improvements. The relative weight of 75 percent for 'CAPEX-conv.' can be explained in terms of the risk for investors, as substantial financial resources are required initially for the setup of a conversion plant, which are expected to be carried by a single or a few investors such as banks or co-operatives. On the other hand, the costs other than for the upgrading and conversion technologies, and the related risks are carried by many stakeholders, such as land owners, farmers and contractors. Furthermore, given that the capital costs were proportionally lower, while the operational costs were proportionally higher, the experts allocated a relative weight of 83 percent to the 'Least OPEX-other' and 17 percent to 'Least CAPEX-other'.

The second-ranked sub-criterion, based on its cumulative weight after IRR, representing more than 18 percent, is 'Direct employment creation potential I'. This translates into 73 percent in relative weight of the socio-economic potential main criterion, while 'Best DECP II' and 'Best DECP III' account for 18 and 8 percent respectively of this main criterion in relative weight.

The relatively low weight for the main criterion 'environmental impact' can be explained by the perception of the experts that any of the given LBSs would represent an improvement compared with the current South African energy mix in terms of environmental impact. Particularly the cumulative weight of less than one percent for 'Least GWP' can be explained by this thinking, as more than 90% of the current energy mix is based on using coal as an energy source. Another reason for 'Least GWP' receiving a relatively low ranking was the financial compensation of the cleaner development mechanism (CDM, the so-called 'carbon credits'). Thus, those LBSs that do well in terms of GWP also benefit in financial-economic terms. Given the local character of the LBSs, great emphasis was given to the local environmental impact criteria, which account for more than 80 percent of the environmental impact main criterion.

7.4.6 Synthesising of information – results

The step following the weighting exercise encompassed multiplying the set of weights with the relative performance of each LBS against the said criteria to present a weighted score for the said LBS against the particular criteria. The aggregated final score for all criteria for each alternative facilitated a ranking of the LBSs. The detailed results thereof for each respective biomass procurement area can be found in Annexure 66-69.

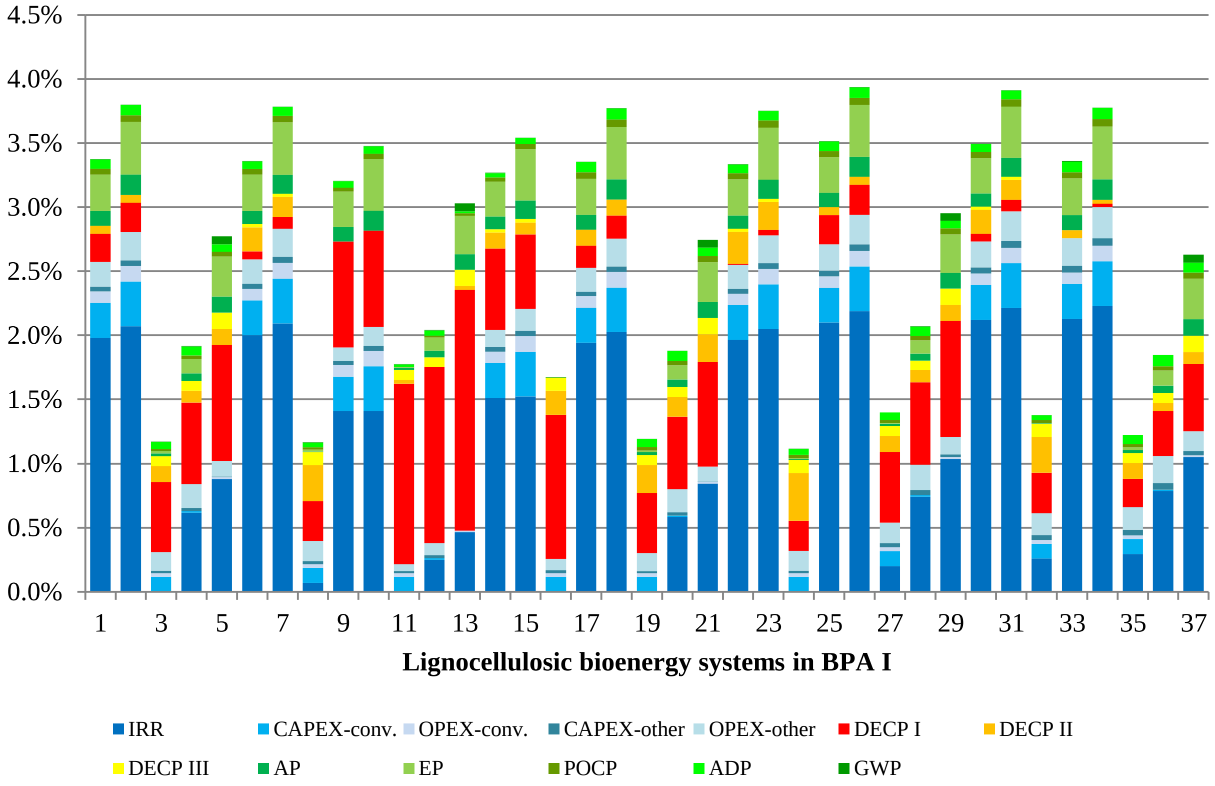

Figure 64: Aggregated, weighted scores of LBSs in BPA I

For LBS key, refer to Figure 11

Notes:

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

Figure 64, above, shows the aggregated, weighted scores for the 37 LBSs in BPA I, suggesting that LBS 26 may be recommended to the public decision makers of the CWDM. LBS 26 exhibits the highest overall ranking on the ratio scale, with 3.94%; followed by LBS 31, with 3.91%; and by LBS 2, with 3.80%. The direct gasification of biomass (Bioenergy Conversion System II, refer to section 5.8.5) is common to the top-eight-ranked LBSs, which differ only in terms of the harvesting system they use. LBS 26 deploys a feller-buncher for harvesting and a forwarder for the primary transportation of the biomass to the roadside (harvesting system III, refer to section 5.3.3). There, the biomass is comminuted (section 5.4.1) and then transported in containers to the central conversion unit.

The bottom-ranked seven LBSs (LBSs 3, 8, 19, 24, 27, 32 and 35) each have an aggregated weighted score of less than 1.40 percent and have BCS III as the bioenergy system common to all of them, namely centralised pyrolysis combined with a combustion (boiler-steam-turbine) system (refer to section 5.8.6). The full ranking of the LBSs based on the weighted scores for all biomass procurement areas are to be found in Table 55, below.

Almost 56 percent of LBS 26's aggregated weighted score is accounted for by its internal rate of return, while the other financial-economic criteria contribute another 20% to its overall result. Thus, the financial-economic main criteria account for a total of around 75% of LBS 26's aggregated weighted scores. Accordingly, it exhibits weighted scores in terms of its socio-economic potential and environmental impact criteria of 8 and 18 percent respectively. Similar profiles in terms of weighted scores were given to the second- to seventh-ranked LBSs, all having BCS II in common (refer to section 5.8.5).

LBS 37, which performed best in terms of aggregated, unweighted scores, was ranked 23rd (2.63%) after the weighting of the scores, showing a distribution of scores for the main criteria 'Financial-economic viability', 'Socio-economic potential' and 'Environmental impact' of 48, 28 and 24 percent respectively. In comparison, top-ranked LBS 26 in terms of weighted scores is ranked 11th in terms of unweighted scores, exhibiting a distribution of scores for the main criteria 'Financial-economic viability', 'Socio-economic potential' and 'Least environmental impact' of 54, 6 and 40 percent respectively.

A similar outcome as for biomass procurement area I can be seen in Figure 65, which illustrates the aggregated, weighted scores of the 37 LBSs for BPA II. Again, LBS 26 exhibits the best weighted performance, with a score of 3.75 percent, with more than 70 percent of its aggregated score being attributable to the financial-economic criteria. The socio-economic criteria contribute another 9 percent, while the environmental criteria contribute almost 20 percent. The single criterion contributing the most to LBS 26's overall result is 'Best IRR', accounting for nearly 53 percent. LBSs 2, 18 and 31 have similar weighted-score profiles, and perform similarly, with scores of 3.63, 3.62 and 3.59 percent respectively. Similar to BPA I, the top ten are dominated by alternatives that deploy the same biomass upgrading and conversion system, BCS II.

Table 55: Ranking of LBSs based on experts' weighted scores

Ranking	BPA I		BPA II		BPA III		BPA IV	
	LBS	AWS	LBS	AWS	LBS	AWS	LBS	AWS
1	26	3.935%	26	3.745%	13	3.592%	13	3.568%
2	31	3.912%	2	3.627%	26	3.507%	26	3.494%
3	2	3.800%	18	3.616%	31	3.414%	18	3.420%
4	7	3.785%	31	3.595%	2	3.404%	2	3.420%
5	34	3.776%	10	3.545%	10	3.386%	31	3.396%
6	18	3.770%	34	3.542%	18	3.379%	29	3.361%
7	23	3.752%	7	3.483%	15	3.337%	10	3.353%
8	15	3.542%	23	3.471%	7	3.312%	7	3.327%
9	25	3.513%	15	3.458%	34	3.303%	23	3.322%
10	30	3.493%	25	3.337%	23	3.287%	34	3.313%
11	10	3.478%	9	3.240%	29	3.275%	15	3.285%
12	1	3.375%	30	3.212%	25	3.184%	21	3.220%
13	6	3.360%	13	3.206%	9	3.172%	5	3.191%
14	33	3.359%	1	3.185%	30	3.156%	25	3.181%
15	17	3.353%	14	3.169%	14	3.139%	9	3.150%
16	22	3.333%	17	3.161%	21	3.119%	1	3.104%
17	14	3.269%	33	3.107%	5	3.118%	17	3.102%
18	9	3.205%	6	3.067%	17	3.075%	14	3.099%
19	13	3.030%	22	3.049%	1	3.070%	30	3.090%
20	29	2.952%	29	2.954%	22	3.012%	6	3.018%
21	5	2.773%	21	2.793%	6	3.000%	22	3.010%
22	21	2.745%	5	2.769%	33	2.941%	37	2.975%
23	37	2.631%	37	2.551%	37	2.904%	33	2.968%
24	28	2.069%	12	2.327%	12	2.393%	12	2.380%
25	12	2.042%	28	2.166%	28	2.193%	28	2.216%
26	4	1.918%	4	2.049%	4	2.100%	4	2.119%
27	20	1.881%	20	2.020%	20	2.091%	20	2.086%
28	36	1.849%	36	1.902%	36	1.960%	36	1.982%
29	11	1.776%	11	1.833%	11	1.886%	11	1.840%
30	16	1.674%	27	1.809%	16	1.865%	27	1.801%
31	27	1.399%	16	1.786%	27	1.840%	16	1.797%
32	32	1.378%	32	1.633%	32	1.733%	32	1.662%
33	35	1.223%	3	1.579%	3	1.606%	3	1.594%
34	19	1.193%	35	1.566%	35	1.605%	35	1.594%
35	3	1.173%	19	1.555%	19	1.596%	19	1.565%
36	8	1.166%	8	1.455%	8	1.542%	8	1.508%
37	24	1.116%	24	1.440%	24	1.505%	24	1.489%

Notes:
LBS Lignocellulosic bioenergy system
BPA Biomass procurement area
AWS Aggregated weighted scores
For LBS key, refer to Figure 11

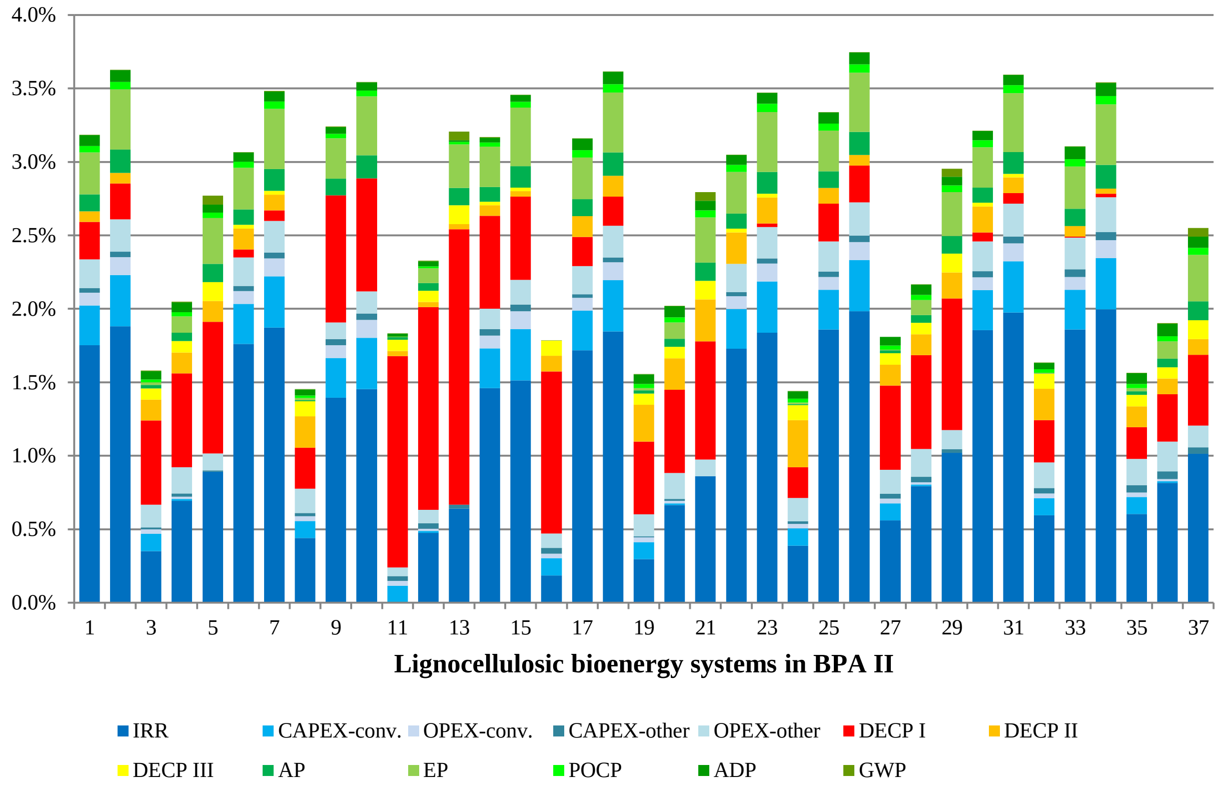

Figure 65: Aggregated, weighted scores of LBSs in BPA II

For LBS key, refer to Figure 11

Notes:

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

With a score of 1.44%, lowest-ranked LBS 24 is more than 2.5 times less favourable than highest-ranked LBS 26. While LBS 24 performs relatively weakly in terms of the environmental impact criteria, which account for only seven percent of its overall performance, its socio-economic performance contributes 44 percent, and its financial-economic weighted scores contribute the remaining 50 percent to its overall result. Bioenergy conversion system III (refer to section 5.8.6) is common to all bottom-nine-ranked bioenergy system alternatives, including LBS 24.

Compared with the former two biomass procurement areas, for which LBS 26 is ranked top, the weighting of the scores for BPA III resulted in LBS 13 being the top-ranked alternative, as illustrated in Figure 66. With a weighted score of 3.59%, LBS 13 leads the ranking, followed by LBS 26 (3.51%), LBS 31 (3.41%) and LBS 2 (3.40%). Similar to biomass procurement area II, nine of the top-ten-ranked lignocellulosic bioenergy systems in BPA III deploy bioenergy conversion system II.

Overall, 58 percent of LBS 13's aggregated weighted score is accounted for by its socio-economic performance, while 'Financial-economic viability' and 'Least environmental impact' each contribute 21 percent to its overall score. A very different profile of the aggregated, weighted scores characterises second-ranked LBS 26, with 72% being contributed by its financial-economic viability, 10% by its socio-economic potential, and the remaining 18% by its performance in terms of the 'Least environmental impact' main criterion. This difference in profile between the first- and second-ranked LBSs becomes more apparent when comparing their respective absolute values in terms of 'IRR' and 'DECP I'. LBS 13 has an IRR of 1.76%, less than 6 times the IRR of LBS 26 (10.96%) (refer to Chapter 6). Yet, LBS 13 has a direct employment creation potential for category I of 403, compared with LBS 26's 118, with this criterion contributing nearly 54 percent to the overall score for LBS 13 and only 6.6 percent to the overall result of second-ranked LBS 26. This can be explained, *inter alia*, by the relatively lower mean annual increments (MAI) of BPAs III and IV compared with the previously discussed biomass procurement areas (refer to section 4.3.2), resulting in more land being required to ensure its bioenergy feedstock supply and, thus, in more labour being required to establish and maintain the SRC plantations prior to harvesting. In addition to this, LBS 13's labour-intensive motor-manual harvesting and manual loading and unloading of the logs used to generate bioenergy (refer to Harvesting System II, section 5.3.2) leads to a considerably higher employment potential, particularly for 'DECP I'.

As illustrated in Figure 67, BPA IV's LBS with the highest aggregated, weighted scores is LBS 13 (3.57%), followed by LBS 26 (3.49%), LBS 18 and LBS 2 (both with 3.42%). Similar to the previous biomass procurement area, the dominant main criterion is socio-economic potential, contributing nearly 53% to LBS 13's overall result, with financial-economic viability and least environmental impact adding 21 and 22 percent respectively.

Again, LBS 13 scores highest in terms of 'DECP I', which contributes nearly 53 percent to LBS 13's aggregated result. Of its overall, aggregated weighted score, 21% is determined by its financial-economic performance, 57% by its socio-economic performance, and 22% by its environmental impact performance. Second-ranked LBS 26 exhibits a considerably different profile, with 73% of its overall score being contributed by its financial-economic performance and the weighted scores for the socio-economic criteria and environmental impact criteria contributing 9% and 18% respectively. As with the other biomass procurement areas, with LBSs 2, 7, 10, 18, 23, 26, 31and 34 in the top-ten, BPA IV is dominated by alternatives deploying bioenergy conversion system II.

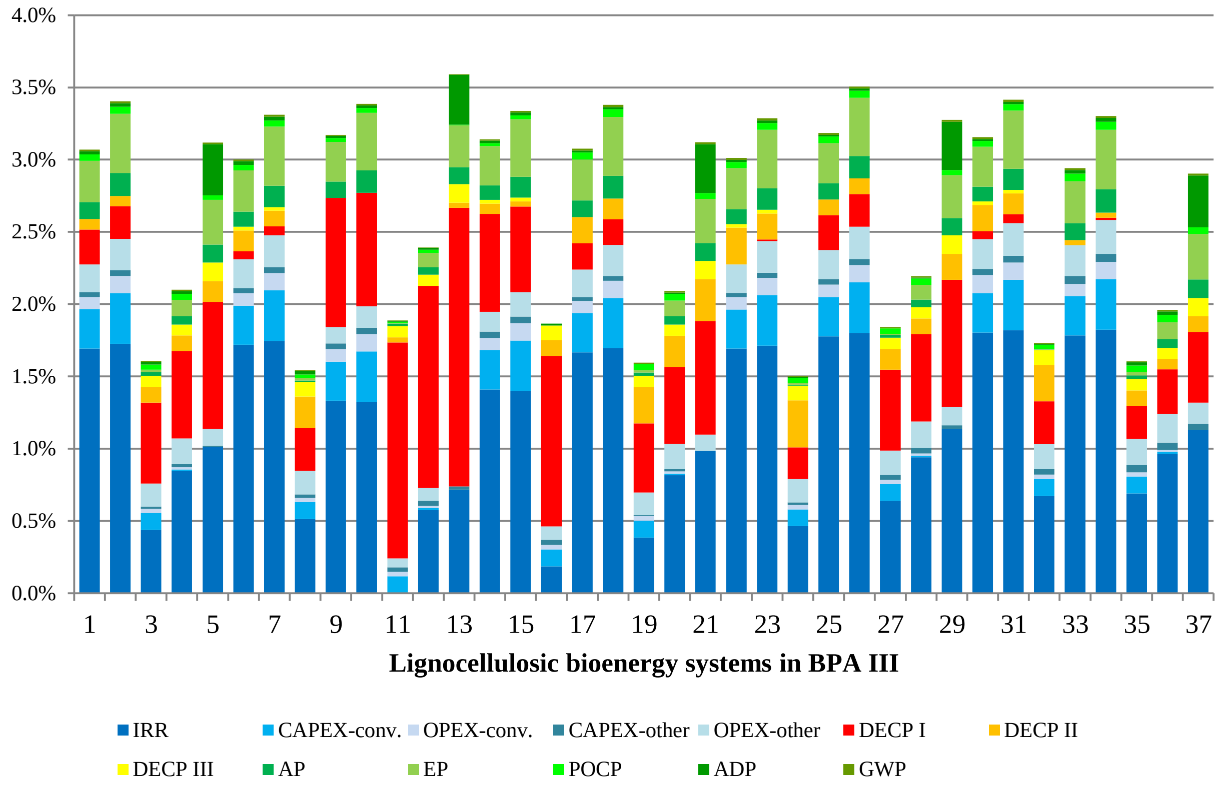

Figure 66: Aggregated, weighted scores of LBSs in BPA III

For LBS key, refer to Figure 11

Notes:

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

With aggregated scores of less than 1.84 percent, LBSs 3, 8, 11, 16, 19, 24, 27, 32 and 35 are least favourable, all having BCS III in common and featuring relatively weak performances in terms of financial-economic and environmental impacts.

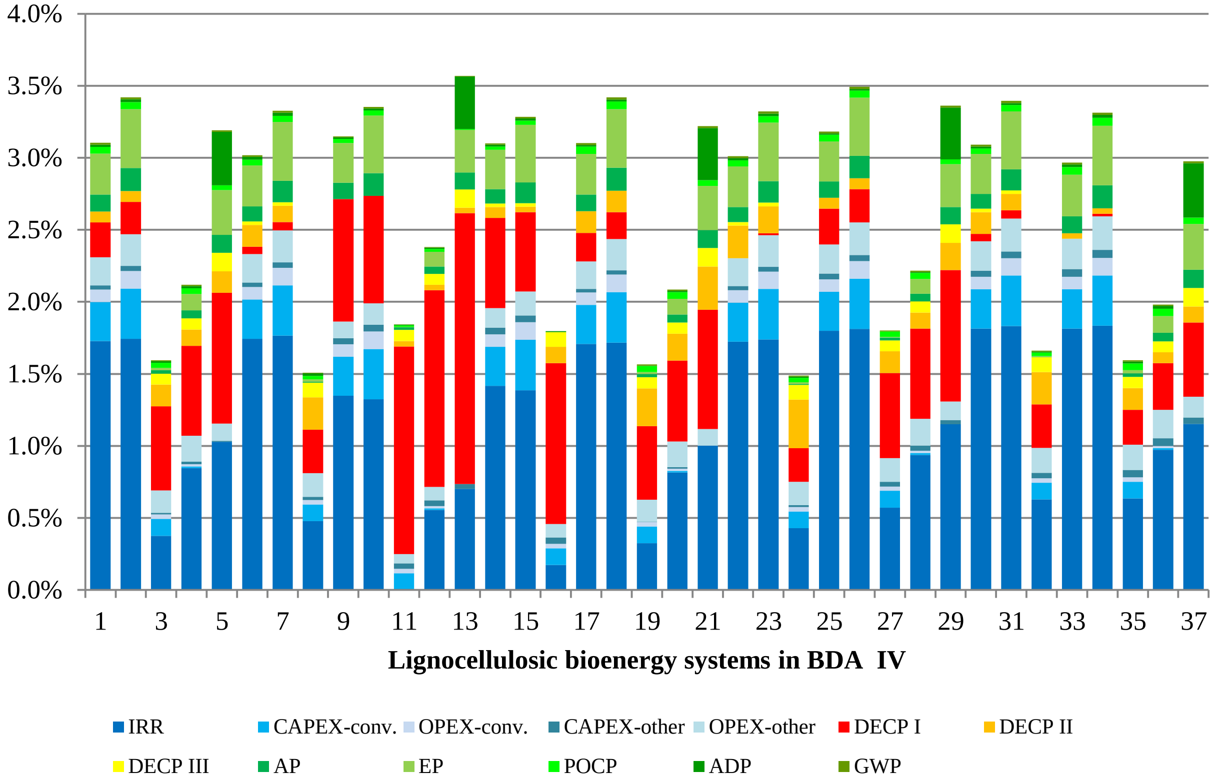

Figure 67: Aggregated, weighted scores of LBSs in BPA IV

For LBS key, refer to Figure 11

Notes:

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

7.5 Maximisation of main criteria/sensitivity analysis

Although the expert group reached consensus on a set of weights for the selected criteria and resulting trade-offs, after having engaged in a discussion on the LBSs and their compositions, the final decision makers and other stakeholders may have differing interests and goals, which may result in a preference for a different set of weights. This section investigates the impact of maximising the relative weight of a particular main criterion, i.e. by omitting the other two main criteria, assuming that there is general agreement among the stakeholders on the relative weights for the sub-criteria provided by the expert group. The new rankings of the LBSs, based on the maximised main criterion, are then compared against the 'original' rankings of the LBSs, based on the set of weights provided by the expert group, taking all of the main criteria into account (refer to section 7.4.5).

7.5.1 Maximisation of financial-economic main criterion

Although the expert group had already emphasised the importance of the financial-economic viability by allocating nearly 60% to this main criterion, a slightly different ranking results when maximising the relative weight of the financial-economic main criterion. Figure 68, below, shows the aggregated, weighted scores for the LBSs (refer also to Annexure 71), assuming a relative weight of 100% for the financial-economic main criterion, while retaining the relative weights of the sub-criteria (IRR: 72%; CAPEX-conv.: 11%; OPEX-conv.: 4%; CAPEX-other: 2%; OPEX-other: 10%).

In terms of the maximised financial-economic main criterion, LBS 34 performs best across all four biomass procurement areas, followed by LBSs 31 and 26, while LBSs 11, 16 and 19 show the least favourable results (refer also to Annexure 74). In comparison, based on the 'original' ranking, LBS 34 comes 5^{th}, 6^{th} 9^{th} and 10^{th} in BPAs I-IV respectively, with LBS 26 and LBS 13 ranking top in BPAs I-II and II-IV respectively (refer to Table 55).

Thus, in the case of BPAs I and II, if the final decision maker were to follow the expert group's recommendation in selecting LBS 26 instead of LBS 34, the result would be lower efficiency in terms of financial-economic viability, greater environmental impact, and improved socio-economic potential, as is shown in Table 56. For instance, selecting LBS 26 would result in a relatively lower IRR of between one and two percent, depending on the biomass procurement area concerned. Taking the net present value (NPV) of the LBSs into consideration (refer to Annexure 47), selecting LBS 26 instead of LBS 34 would result in a loss of profitability of around R16 million over a period of 25 years in the case of BPA I (R331m vs R347m), and over 27 years in the case of BPA II (R380m vs R396m). While CAPEX-conv. and OPEX-conv. would remain the same, since both alternatives deploy the same biomass upgrading and conversion systems, LBS 26's CAPEX-other is 20 and 66 percent higher than LBS 34's CAPEX-other (for BPAs I and II respectively), and its OPEX-other is six and seven percent higher. Also, from an environmental impact point of view, the selection of LBS 26 instead of LBS 34 may have a negative effect, with an increased acidification and eutrophication potential of up to five percent, an increased photochemical ozone creation potential of around two percent, and an abiotic depletion potential of 23 to 35 percent. In BPA's I and II, LBS 34 exhibits a global warming potential of around zero and 214 tonnes respectively of CO_2-equivalent, compared with LBS 26's global warming potential of 1 048 and 1 596 t CO_2-equiv. From a socio-economic perspective, however, selecting LBS 26 would be favourable, creating 30 to 38 more jobs in terms of 'DECP I', with one more jobs in terms of 'DECP II', and the same number of jobs created for 'DECP III'.

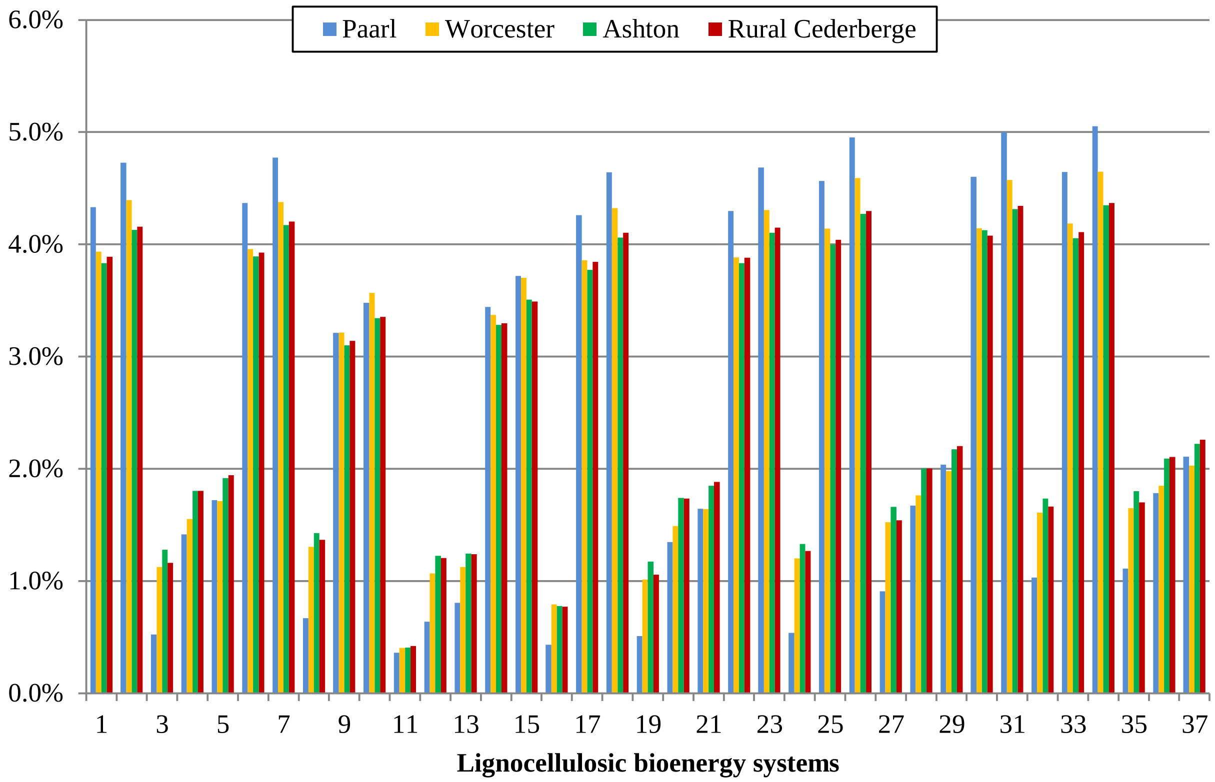

Figure 68: Aggregated weighted scores of LBSs, considering only financial-economic criteria

For LBS key, refer to Figure 11

LBS 13, on the other hand, is positioned at the top of the 'original' rankings for BPAs III and IV, but when taking only the financial-economic criteria into account, it is positioned 33rd and 32nd respectively. With an IRR of 1.36% for BPA III and 1.42% for BPA IV, LBS 13 is around six to seven times less profitable than LBS 34's 10.13% for BPA III and 8.25% for BPA IV. In absolute terms, for BPAs III and IV respectively, LBS 13 exhibits an NPV of minus R28 million and minus R26 million, compared with LBS 34's NPV of R322 million and R291 million. LBS 13's significantly lower profitability can be explained by its considerably higher costs. Its CAPEX- and

OPEX-conv., for instance, are more than six and four times respectively greater than the respective values for LBS 34. Also, LBS 13's CAPEX- and OPEX-other are at least 2.5 times greater than those of LBS 34.

Table 56: Comparison, top-ranked LBSs – complete set of weights vs solely financial-economic criteria

Biomass procurement area	I	II	III	IV	I	II	III	IV
Ranking of LBSs based on:	**Complete set of weights**				**Solely financial-economic criteria**			
LBS	**26**	**26**	**13**	**13**	**34**			
Weighted score – complete set of weights[a]	3.94	3.75	3.59	3.57	3.78	3.54	3.30	3.31
Position after ranking	1				5	6	9	10
Weighted score – solely financial-economic criteria[b]	4.95	4.59	1.25	1.24	5.05	4.65	4.35	4.37
Position after ranking	3	2	33	32	1			
Absolute and relative comparison based on selected criteria								
IRR (%)[c]	10.96	15.15	1.36	1.42	11.18	15.26	10.13	8.25
Loss/gain (%)	*98%*	*99%*	*13%*	*17%*	*100%*			
NPV (R million)[d]	331	380	-28	-26	347	396	322	291
Loss/gain (%)	*95%*	*96%*	*-9%*	*-9%*	*100%*			
CAPEX-conv. (R million)[e]	63	63	398	398	63	63	63	63
Loss/gain (%)	*100%*	*100%*	*632%*	*632%*	*100%*			
OPEX-conv. (R million)[f]	66	66	281	281	66	66	66	66
Loss/gain (%)	*100%*	*100%*	*423%*	*423%*	*100%*			
CAPEX-other (R million)[g]	138	59	113	66	115	35	42	22
Loss/gain (%)	*120%*	*166%*	*272%*	*300%*	*100%*			
OPEX-other (R million)[h]	231	246	736	750	218	230	279	291
Loss/gain (%)	*106%*	*107%*	*263%*	*258%*	*100%*			
DECP I[i]	95	107	429	403	65	69	81	81
Loss/gain (%)	*146%*	*155%*	*530%*	*498%*	*100%*			
DECP II[i]	5	4	3	3	4	3	3	3
Loss/gain (%)	*125%*	*133%*	*100%*	*100%*	*100%*			
DECP III[i]	2	2	7	7	2	2	2	2
Loss/gain (%)	*100%*	*100%*	*350%*	*350%*	*100%*			
AP (t SO_2-equivalent)[j]	86	86	126	124	83	82	86	83
Loss/gain (%)	*104%*	*105%*	*152%*	*151%*	*100%*			
EP (t phosphate-equivalent)[k]	22	22	32	31	21	21	21	21
Loss/gain (%)	*105%*	*105%*	*152%*	*148%*	*100%*			
POCP (t ethene-equivalent)[l]	5.3	5.2	19.1	17.3	5.2	5.1	5.1	5.2
Loss/gain (%)	*102%*	*102%*	*375%*	*333%*	*100%*			
ADP fossil (gigajoule)[m]	20.1	19.4	69.9	62.6	16.3	14.3	14.8	14.6
Loss/gain (%)	*123%*	*135%*	*473%*	*430%*	*100%*			
GWP (t CO_2-equivalent)[n]	1 048	1 596	-32 709	-32 884	1	214	936	958
Loss/gain (%)	*104 800%*	*746%*	*-3 495%*	*-3 433%*	*100%*			

Notes:

[a] Aggregated, normalised (to sum one), relative weighted score based on set of weights by expert group

[b] Aggregated, normalised (to sum one), relative weighted score based on maximisation of financial-economic main criterion only

[c] Refer also to Annexure 45

[d] Refer also to Annexure 47

[e] Refer also to Annexure 48

[f] Refer also to Annexure 49

[g] Refer also to Annexure 50

h	Refer also to Annexure 52
i	Refer also to Annexure 53
j	Refer also to Annexure 40
k	Refer also to Annexure 41
l	Refer also to Annexure 44
m	Refer also to Annexure 39
n	Refer also to Annexure 42

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

A similar comparison can be made in terms of environmental impact, with LBS 13 showing an AP and EP of around 50 percent greater than LBS 34. In terms of environmental impact, LBS 13's POCP and ADP are at least three and four times respectively greater. Only for global warming potential does LBS 13 show a significantly better result than LBS 34, with a GWP of around minus 32 000 t CO_2-equivalent for LBS 13, compared with a GWP of around 950 t CO_2-equivalent for LBS 34. Again, this can be explained by BCS V's carbon storage and sink potential, which involves adding the biochar to soil.

From a socio-economic perspective, however, LBS 13 exhibits significantly better results than LBS 34. With LBS 13's more than 400 jobs created compared with LBS 34's approximately 80, LBS 13's performance in terms of 'DECP I' is around five times greater, and 3.5 times more employment is created in terms of 'DECP III', while the same number of jobs created is expected for 'DECP II'.

7.5.2 Maximisation of socio-economic main criterion

If the LBSs were to be assessed solely in terms of their socio-economic potential, or more specifically, in terms of their direct employment creation potential, while still maintaining the relative weights of the sub-criteria ('DECP I': 73%, 'DECP II': 19% and 'DECP III': 8%), the ranking of the LBSs would be considerably different compared with the 'original' ranking, as is illustrated in Figure 69 (refer also to Annexure 72). Across all biomass procurement areas, LBS 13 leads the ranking, with relative scores of between 8.16 and 8.39 percent, followed by LBSs 11 (6.08-6.44%) and 12 (5.82-5.97%). These LBSs all entail motor-manual harvesting together with the manual loading and unloading of logs, as well as the manual feeding of the mobile chipping and pyrolysis units. LBSs 33 and 34, which are characterised by the relatively high levels of mechanisation of their harvesting systems, are bottom-ranked, showing the lowest weighted scores in terms of socio-economic potential (refer also to Annexure 75). LBS 26, the top-ranked LBS in terms of the expert group's set of weights, is ranked 26 and 28 in BPAs I and II respectively. No comparison is required for BPA's III and IV, since LBS 13 also leads the ranking in these areas, based on the full set of weighted scores. Table 57 compares LBS 26 and LBS 13 in terms of ranking, as well as in terms of the selected key criteria.

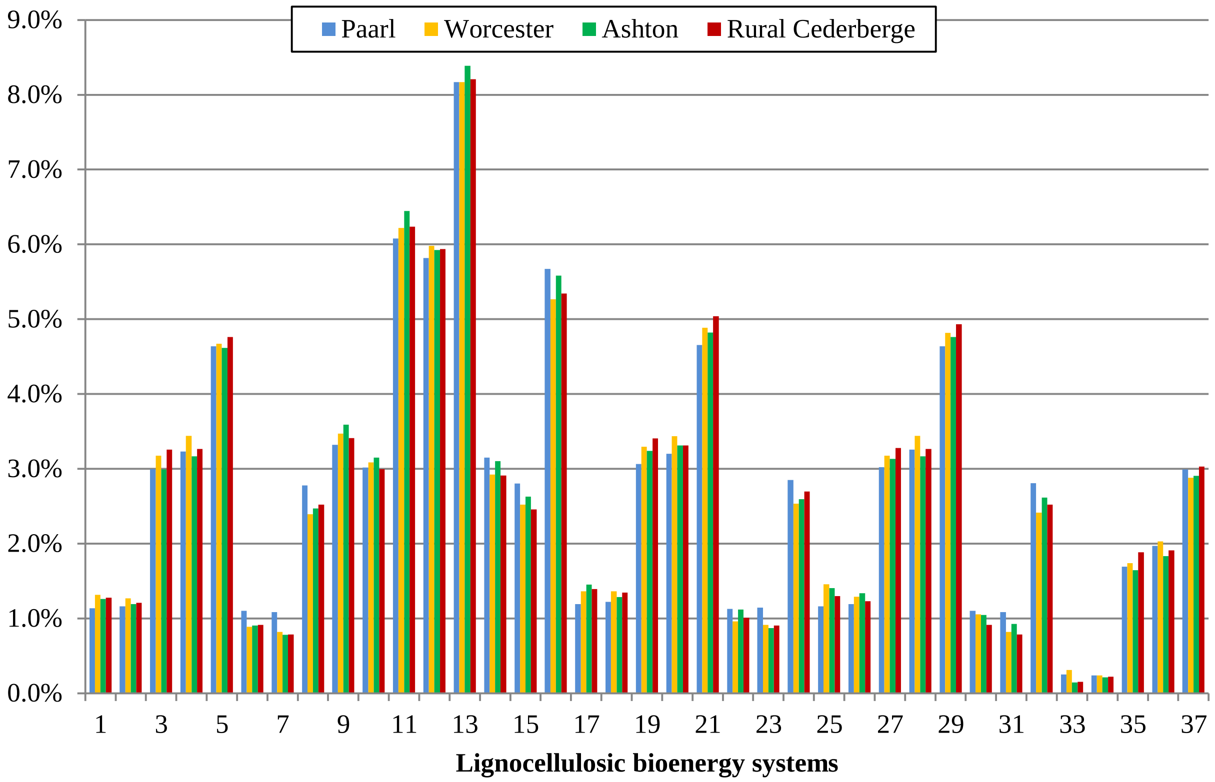

Figure 69: Aggregated weighted scores of LBSs, considering only socio-economic criteria

For LBS key, refer to Figure 11

LBS 26's internal rate of return of 10.96% (BPA I) and 15.15% (BPA II), compared with LBS 13's 1.76% and 3.54% respectively, make it considerably more profitable, which is further highlighted when comparing LBS 26's NPVs for BPAs I and II of R331 and R380 million respectively, compared with LBS 13's R2 and R116 million respectively. This is, *inter alia,* the result of the significantly lower capital required, as well as the lower operating costs. Furthermore, other than in respect of global warming potential, LBS 26 is more environmentally friendly than LBS 13, having a 30 percent lower AP and EP and around 60 to 70 percent lower POCP and ADP. Since LBS 13 uses only bio-oil to generate electricity, with the biochar being used as a soil additive, a considerably negative global warming potential of around 35 000 t CO_2-equivalent is recorded for it, while LBS 26 has a GWP of 1 048 and 1 596 t CO_2-equivalent. In terms of 'DECP I' and 'DECP III', LBS 13 has a 3.5 times greater potential in BPAs I and II than LBS 26, while the latter has a 25% higher potential in terms of 'DECP II' than the former.

Table 57: Comparison, top-ranked LBSs – complete set of weights vs solely socio-economic criteria

Biomass procurement area	I	II	III	IV	I	II	III	IV
Ranking of LBSs based on:	**Complete set of weights**				**Solely socio-economic criteria**			
LBS	**26**	**26**	**13**	**13**	**13**			
Weighted score – complete set of weights[a]	3.94	3.75	3.59	3.57	3.03	3.21	3.592	3.57
Position after ranking	1				19	13	1	1
Weighted score – solely socio-economic criteria[b]	1.19	1.29	8.34	8.21	8.17	8.17	8.34	8.21
Position after ranking	26	28	1	1	1			
Absolute and relative comparison based on selected criteria								
IRR (%)[c]	10.96	15.15	1.36	1.42	1.76	3.54	1.36	1.42
Loss/gain (%)	623%	428%	100%	100%	*100%*			
NPV (R million)[d]	331	380	-28	-26	2	116	-28	-26
Loss/gain (%)	15 168%	328%	100%	100%	*100%*			
CAPEX-conv. (R million)[e]	63	63	398	398	398	398	398	398
Loss/gain (%)	16%	16%	100%	100%	*100%*			
OPEX-conv. (R million)[f]	66	66	281	281	281	281	281	281
Loss/gain (%)	24%	24%	100%	100%	*100%*			
CAPEX-other (R million)[g]	138	59	113	66	289	96	113	66
Loss/gain (%)	48%	61%	100%	100%	*100%*			
OPEX-other (R million)[h]	231	246	736	750	527	604	736	750
Loss/gain (%)	44%	41%	100%	100%	*100%*			
DECP I[i]	95	107	429	403	333	379	429	403
Loss/gain (%)	29%	28%	100%	100%	*100%*			
DECP II[i]	5	4	3	3	4	3	3	3
Loss/gain (%)	125%	133%	100%	100%	*100%*			
DECP III[i]	2	2	7	7	7	7	7	7
Loss/gain (%)	29%	29%	100%	100%	*100%*			
AP (t SO_2-equivalent)[j]	86	86	126	124	122	124	126	124
Loss/gain (%)	70%	69%	100%	100%	*100%*			
EP (t phosphate-equivalent)[k]	22	22	32	31	31	31	32	31
Loss/gain (%)	71%	71%	100%	100%	*100%*			
POCP (t Ethene-equivalent)[l]	5.3	5.2	19.1	17.3	16.2	17.6	19.1	17.3
Loss/gain (%)	33%	30%	100%	100%	*100%*			
ADP fossil (gigajoule)[m]	20.1	19.4	69.9	62.6	56.3	61.4	69.9	62.6
Loss/gain (%)	36%	32%	100%	100%	*100%*			
GWP (t CO_2-equivalent)[n]	1 048	1 596	-32 709	-32 884	-36 178	-34 988	-32 709	-32 884
Loss/gain (%)	-3%	-5%	100%	100%	*100%*			

Notes:

[a] Aggregated, normalised (to sum one), relative weighted score based on weights set by expert group

[b] Aggregated, normalised (to sum one), relative weighted score based on maximisation of financial-economic main criterion only

[c] Refer also to Annexure 45

[d] Refer also to Annexure 47

[e] Refer also to Annexure 48

f	Refer also to Annexure 49
g	Refer also to Annexure 50
h	Refer also to Annexure 52
i	Refer also to Annexure 53
j	Refer also to Annexure 40
k	Refer also to Annexure 41
l	Refer also to Annexure 44
m	Refer also to Annexure 39
n	Refer also to Annexure 42

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than of biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than of biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

7.5.3 Maximisation of environmental impact main criterion

The ranking of the LBSs changes, as with the other two main criteria, when assessing them solely against the third main criterion 'Least environmental impact' while maintaining the weights of their sub-criteria (AP: 22%; EP: 53%; POCP: 9%; ADP: 14%; and GWP: 2%). In BPAs I and II, LBS 34 is ranked top, with weighted scores of 4.50 and 4.52 percent respectively, followed by LBS 18 (4.47 and 4.39%) and LBS 26 (4.46 and 4.38%) (for the full ranking refer also to Annexure 76). The top eight LBSs all deploy BCS II (refer to section 5.8.5), which is characterised by its relatively good overall conversion efficiency, resulting in less biomass being required and consequently less land being required, with lower emissions at each stage of the bioenergy system. The relatively good overall harvesting efficiency, as well as the relatively high biomass productivity and the increase in carbon stock for the first two biomass procurement areas lead to the favourable performances of LBS 34.

In BPAs III and IV, on the other hand, LBS 37 is ranked top, with weighted scores of 5.42 and 5.54 percent respectively, followed by LBS 21 (5.12 and 5.28%) and LBS 5 (5.11 and 5.25%). Including the fourth- and fifth-ranked LBS 5 and LBS 29, the top five-ranked LBSs employ, with BCS V, the same bioenergy conversion technology (refer to section 5.8.8), where only bio-oil is used to generate electricity, while the bio-char is sold as a soil additive. This leads to a significantly negative GWP, resulting in scores around six times greater than the LBS's average GWP. As discussed in section 4.3.3.3, in general, it can be said that along with lower biomass productivity, the carbon storage capacity of the SRC plantations is also reduced. Thus, while in BPAs I and II, the carbon stock change contributes positively to all LBSs in terms of GWP, it has a lesser effect in BPAs III and IV. This emphasises the effect of applying bio-char to the soil, resulting in a change of the ranking of the LBSs, with a preference for the LBSs deploying BCS V. Across all biomass procurement areas, LBSs 3, 8, 11, 16, 19, 24, 27, 32 and 35 are the bottom-ranked alternatives, all having BCS III in common, which is characterised by its relatively low overall conversion efficiency, resulting in relatively higher emissions.

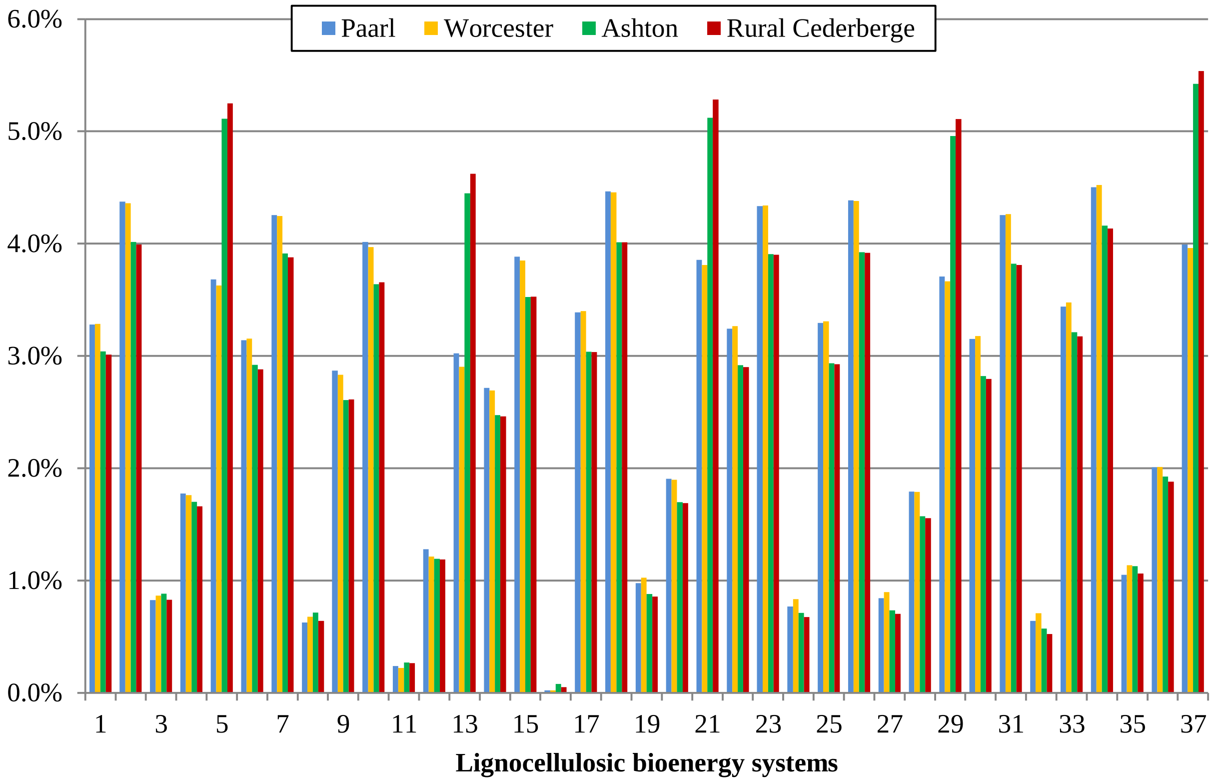

Figure 70: Aggregated weighted scores of LBSs, considering only environmental impact criteria

For LBS key, refer to Figure 11

A comparison of the ‘expert's’ top-ranked LBSs 13 and 26 with LBSs 34 and 37 is given in

Table *58*, below. Since LBS 34 is ranked top in BPAs I and II, not only from a ‘Least environmental impact’ perspective, but also from a financial-economic perspective, no further discussion on the comparison of LBS 26 with LBS 34 is necessary. In BPAs III and IV, however, in terms of ‘Least environmental impact’, LBS 37 is ranked top, while LBS 13 is ranked top when taking all weighted criteria into consideration. With scores of 4.65 (BPA III) and 4.13% (BPA IV), LBS 37 has an IRR around three times greater than LBS 13 (1.36 and 1.42% respectively). LBS 37 generates an NPV of R209 million (BPA III) and R187 million (BPA IV), while LBS 13 exhibits a negative NPV of R28 (BPA III) and R26 million (BPA IV). Since both alternatives deploy the same bioenergy conversion technologies, no differences are expected for ‘CAPEX-conv.’ and ‘OPEX-conv’.

Table 58: Comparison, top-ranked LBSs – complete set of weights vs solely ‘Least environmental impact’ criteria

Biomass procurement area	I	II	III	IV	I	II	III	IV
Ranking of LBSs based on:	**Complete set of weights**				**Solely least environmental impact criteria**			
LBS	**26**	**26**	**13**	**13**	**34**	**34**	**37**	**37**
Weighted score – complete set of weights[a]	3.94	3.75	3.59	3.57	3.78	3.54	2.90	2.98
Position after ranking	1				5	6	23	22
Weighted score – solely ‘Least environmental impact’ criteria[b]	4.39	4.38	4.44	4.62	4.50	4.52	5.42	5.54
Position after ranking	3	3	5	5	1			
Absolute and relative comparison based on selected criteria								
IRR (%)[c]	10.96	15.15	1.36	1.42	11.18	15.26	4.65	4.13
Loss/gain (%)	98%	99%	29%	34%	*100%*			
NPV (R million)[d]	331	380	-28	-26	347	396	209	187
Loss/gain (%)	95%	96%	-13%	-14%	*100%*			
CAPEX-conv. (R million)[e]	63	63	398	398	63	63	398	398
Loss/gain (%)	100%	100%	100%	100%	*100%*			
OPEX-conv. (R million)[f]	66	66	281	281	66	66	281	281
Loss/gain (%)	100%	100%	100%	100%	*100%*			
CAPEX-other (R million)[g]	138	59	113	66	115	35	71	39
Loss/gain (%)	120%	166%	159%	167%	*100%*			
OPEX-other (R million)[h]	231	246	736	750	218	230	453	469
Loss/gain (%)	106%	107%	162%	160%	*100%*			
DECP I[i]	95	107	429	403	65	69	167	167
Loss/gain (%)	146%	155%	257%	241%	*100%*			
DECP II[i]	5	4	3	3	4	3	5	5
Loss/gain (%)	125%	133%	60%	60%	*100%*			
DECP III[i]	2	2	7	7	2	2	7	7
Loss/gain (%)	100%	100%	100%	100%	*100%*			
AP (t SO_2-equivalent)[j]	86	86	126	124	83	82	116	115
Loss/gain (%)	104%	105%	109%	108%	*100%*			
EP (t phosphate-equivalent)[k]	22	22	32	31	21	21	30	29
Loss/gain (%)	105%	105%	107%	107%	*100%*			
POCP (t ethene-equivalent)[l]	5.3	5.2	19.1	17.3	5.2	5.1	8.1	8.1
Loss/gain (%)	102%	102%	236%	214%	*100%*			
ADP fossil (gigajoule)[m]	20.1	19.4	69.9	62.6	16.3	14.3	24.7	24.1
Loss/gain (%)	123%	135%	283%	260%	*100%*			
GWP (t CO_2-equivalent)[n]	1 048	1 596	-32 709	-32 884	1	214	-34 258	-34 230
Loss/gain (%)	104 800%	746%	95%	96%	*100%*			

Notes:

[a] Aggregated, normalised (to sum one), relative weighted score based on weights set by expert group

[b] Aggregated, normalised (to sum one), relative weighted score based on maximisation of financial-economic main criterion only

[c] Refer also to Annexure 45

[d] Refer also to Annexure 47

e	Refer also to Annexure 48
f	Refer also to Annexure 49
g	Refer also to Annexure 50
h	Refer also to Annexure 52
i	Refer also to Annexure 53
j	Refer also to Annexure 40
k	Refer also to Annexure 41
l	Refer also to Annexure 44
m	Refer also to Annexure 39
n	Refer also to Annexure 42

IRR	Internal rate of return on capital investment
CAPEX-conv.	Capital expenditure on biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure on biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than on biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than on biomass upgrading and conversion technologies
DECP I	Direct employment creation potential providing an income of less than R8 000/month
DECP II	Direct employment creation potential providing an income of R8 000-R24 000/month
DECP III	Direct employment creation potential providing an income of more than R24 000/month
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
GWP	Global warming potential

The lower harvesting efficiency of LBS 13 compared with LBS 37, however, causes a higher cost of at least 60% in terms of 'CAPEX-other' and 'OPEX-other'. While LBS 13's AP and EP are only slightly higher (around 10 percent), considerable differences were recorded for POCP and ADP, being around 2 times and 3.5 to 4 times greater than LBS 37's respective values. For LBS 13, the five percent higher GWP can be explained by the loss of biomass during the motor-manual harvesting operation, resulting in more land being required and, thus, more energy being inputted to supply sufficient biomass.

7.6 Conclusions

In the past, the 'success' of energy systems was driven mostly by financial drivers, leading to fossil fuels as a feedstock being the preferred choice. Major technical, social, political and economic challenges such as the need for security and diversification of energy supplies, the necessity for less reliance on fossil fuels, the uncertainty surrounding oil prices and the rising concerns over environmental degradation and climate change effects, however, have caused this approach to be viewed as unsustainable. This prompted not only the promotion of renewable energy sources but also a more sustainability driven approach in assessing such projects, necessitating more sophisticated measurements and the integration of a wider range of criteria in the decision-making process.

Based on a case study for the Cape Winelands District Municipality (CWDM), Chapters 4 to 6 provide such sophisticated measurements of a wider range of criteria by using, *inter alia*, life-cycle assessment (LCA), geographic information systems (GIS) and multi-period budgeting (MPB). The nature of 37 defined lignocellulosic bioenergy systems (LBSs), which were assessed against five financial-economic, three socio-economic and five environmental key criteria, highlighted the complexity and the trade-offs between the different criteria, constituting a major barrier to the implementation of bioenergy projects.

As shown in this chapter, multi-criteria decision analysis (MCDA) is an approach which can aid overcoming such a decision-making barrier by organising and synthesising the respective information, integrating mixed sets of data and assisting decision makers to place the problem in context and to determine the preferences of the potential stakeholders involved. The analytic hierarchy process (AHP), one of the commonly applied MCDA approaches, was used to identify the most sustainable lignocellulosic bioenergy system (LBS). The initial steps of the AHP included developing a hierarchy of criteria (criteria value tree) and translating and normalising the performances of the considered 37 LBS alternatives into a standardised common language of relative performance, i.e. in so-called scores. The aggregation of these scores for each LBS results in a ranking of the alternatives, with each criterion being equally important. Across all the four investigated biomass procurement areas, the ranking gives preference to those alternatives which deploy bioenergy conversion system V, which is characterised by a mobile pyrolysis system for biomass upgrading into bio-oil and bio-char. Only the former is used to generate electricity, while the latter is used as a soil additive, resulting in exceptionally high scores in terms of 'Least global warming potential', but also in low scores in terms of financial-economic performance, due to the low overall conversion efficiency.

Notwithstanding this, the decision-making problem persisted, as the conflicting nature of some of the criteria, the differing viewpoints of potential stakeholders and the resulting trade-offs were not considered in this phase of the MCDA, requiring an additional phase in which the stakeholder preferences were taken into account by attaching weights to the considered criteria. Hence, based on a discussion of the alternatives and their respective performances in terms of the predefined criteria, aimed at providing insight, a task team consisting of various experts, reflecting the broad spectrum of potential stakeholders, was requested to elicit the relative preferences for the criteria by means of pairwise comparisons using the AHP-based Expert Choice software. No serious conflicts in opinion between the participants were recorded during the discussions and the weighting procedure, resulting in consensus on a set of weights, where the main criterion 'financial-economic viability' received a preference of almost 60%, 'socio-economic potential' nearly 25% and 'least environmental impact' the remainder of almost 16%. The single most important sub-criteria are 'best IRR' and 'direct employment creation potential (DECP) I' with a cumulative weight of around 43 and 18 percent respectively.

The aggregation of the weighted scores to a single indicator allowed a ranking of the lignocellulosic bioenergy systems (LBS), placing LBS 26 at the top in biomass procurement areas (BPA) I and II and second in BPA III and IV. Around 73-74 percent of its aggregated, weighted score derived from its 'Financial-economic viability', around 8-9 percent from its 'Socio-economic potential' and 18-19 percent from its 'Least environmental impact'. Similar profiles to that of LBS 26 are shown for most of the top-ten-ranked alternatives across all biomass procurement areas. With few exceptions, all encompass biomass upgrading and bioenergy conversion system (BCS) II, namely a parallel series of integrated 450Nm^3/h gasifier-gas-turbine systems. Compared with the other bioenergy conversion systems, BCS II is characterised by relatively low capital and operational costs, as well as by good conversion efficiencies. The latter also has an effect on all upstream activities, as less biomass and, thus, less land is needed, resulting in fewer upstream activities and, therefore, in lower operational and capital costs, including for machinery and land.

The results further suggest that the relatively immature fast-pyrolysis technology is currently not a viable option as part of a bio-electricity generation system. Particularly alternatives deploying bioenergy conversion system III (a centralised, stationary pyrolysis plant for biomass upgrading into bio-oil and bio-char combined with a boiler-steam turbine system), show poor results and are at the bottom of the ranking across all biomass procurement areas. This can be explained by its poor overall conversion efficiency, resulting in relatively greater upstream inputs and activities, as well as by its relatively high capital and operational costs for the conversion system. Similar reasons can be given for alternatives deploying bioenergy conversion systems IV and V, which both encompass mobile pyrolysis units for biomass upgrading. To generate electricity, the former uses a centralised, stationary boiler-steam turbine in which both pyrolysis products are combusted, while the latter uses only bio-oil in a direct injection gas turbine system; the bio-char is used as an additive to soil, which effectively works as a form of carbon capture and storage. The only exception represents the bioenergy conversion system V-driven LBS 13, which is ranked top for biomass procurement areas III and IV. In both BPAs, nearly 60% of LBS 13's aggregated, weighted score is contributed by its socio-economic performance, with the remainder being equally contributed by its financial-economic and environmental performance. LBS 13's relatively low harvesting and conversion efficiency causes such a significantly greater demand in terms of human capital, particularly in the low income category, that its aggregated, weighted score is slightly greater than the second-ranked LBS 26.

Two aspects contribute to a different outcome for BPAs III and IV, namely (1) the relatively lower biomass productivity, resulting in more land being required to ensure sufficient biomass feedstock supply and, thus, in more material, machinery and human capital being required, and (2) the relatively lower land value, being one of the main cost factors, resulting in a lower impact in terms of costs on the financial-economic viability, i.e. the tendency of selecting alternatives with a relatively greater conversion efficiency becomes less important as increases in socio-economic potential compensate for a loss in financial-economic viability. However, similar to the first two biomass procurement areas, at least eight of the top-ten-ranked alternatives in BPA III and IV encompass bioenergy conversion system II, the aggregated, weighted score profiles of which represent a more valid reflection of the set of weights given by the expert group. Thus, despite the fact that the ranking of BPAs III and IV suggests that LBS 13 may be the preferred choice, the final decision maker may still select LBS 26, following the prerequisite of financial viability, i.e. if the LBS is not profitable, private investors will not be interested in investing in this particular alternative, which is the case for LBS 13 in BPAs III and IV (NPV of R-28m and R-26m respectively).

However, as discussed in Chapter 3, MCDA does not provide the ‘single right answer’, even within the context of the model used, as the concept of an optimum does not exist in a multi-criteria framework. This was illustrated during the sensitivity analysis of the MCDA results, where each of the main criteria was considered independently, while retaining the relative weights for their respective sub-criteria. When considering solely financial-economic criteria or environmental criteria in the decision-making process, LBS 34 may be the preferred choice ahead of LBS 26 in the case of biomass procurement areas I and II, as it encompasses a more efficient harvesting system (HS) (i.e. HS V) besides BCS II, resulting in greater cost efficiency and a lower environmental impact. However, LBS 34 is also characterised by a lower direct employment creation potential. If, on the other hand, solely socio-economic potential criteria were to be considered for BPAs I and II, LBS 13 would be the preferred choice in BPAs I and II, exhibiting a 3.5 times greater employment potential in the low and high income categories (DECP I and III) than LBS 26. However, this choice would also result in a considerably poorer financial-economic and environmental performance.

As was shown in this chapter, MCDA proves to be an appealing and practical tool that organises and synthesises relevant information in a way that should lead decision makers to feel comfortable and confident about making a decision, as it minimises the potential post-decision regret by ensuring satisfaction that all criteria or factors have been properly taken into account. Particularly when seeking to implement bioenergy systems, it is well suited for integration with performance-data-generating methods such as LCA and complementary financial- and socio-economic assessment methods. It is, however, not the purpose of MCDA to solve a particular decision-making problem. Rather, its purpose is to produce insight in order to help decision makers make better decisions; learn about and understand the problem faced; understand own, other parties' and organisational priorities values and objectives; and through exploring these in the context of the problem, guide them in identifying a preferred course of action and to promote transparency.

8 CHAPTER: CONCLUSIONS, SUMMARY AND RECOMMENDATIONS

8.1 Conclusions

Some projections indicate an increase of more than 300% in global energy demand by 2035 – by that time the daily extraction capacity of crude oil will have declined by 50 million barrels. Despite uncertainties about detail, it is now evident that the world faces the dawn of the second half of the age of oil, when this critical commodity, which plays such a fundamental role in the modern economy, heads into decline, due to natural depletion (Campell, 2012). Financially, this will add further pressure to the price per barrel of crude oil, which has already more than quintupled over the last ten years. In addition, the inability of the environment to maintain its sink function, i.e. the ability to maintain its assimilating capacity without the unacceptable degradation of its future waste-absorbing capacity or other important services, will force world economies to reduce their use of fossil energy sources and to reconsider current energy policies and management. However, the transition to decline threatens to be a time of great international tension. 'Petroleum man' will approach extinction this century and *Homo sapiens* will face major social, political and economic challenges in adapting to these losses.

This has prompted not only a new energy paradigm, from fossil fuels to renewable energy sources, but also a demand for new ways of measuring the viability of energy systems. In the past, the 'success' of energy systems was mostly driven by financial considerations, using monetary assessment methods such as cost-benefit analyses. This led to fossil fuels being the preferred choice; however, the introduction of renewable energies has required a more sustainability-driven approach, necessitating more sophisticated measurements of a wider range of 'success' criteria. Technical efficiency, economic affordability, environmental friendliness and social acceptance, amongst others, are the driving sustainability factors determining the success of renewable energy systems. The resulting complexity, however, constitutes a major barrier to implementation, as much information of a complex and conflicting nature, often reflecting different viewpoints and often changing with time, needs to be processed. Confronted with such a decision-making problem, the public decision makers of the Cape Winelands District Municipality (CWDM) in the Western Cape, South Africa, were prompted to investigate possibilities for implementing local renewable energy systems. By using the CWDM as a case study area, this study aims to illustrate how to aid such a decision-making process by providing quantitative data using the life-cycle assessment (LCA) approach, geographic information systems (GIS), multi-period budgeting and other quantitative assessment methods, and by integrating various considerations using the multi-criteria decision analysis method.

Against this background, bioenergy emerges as a solution that could not only meet a significant amount of the world's constantly increasing energy demand, but that also represents – compared with other available renewable energy sources, including hydro, solar, or wind – the only carbon-based sustainable option for mitigating greenhouse gas emissions. Another advantage of using biomass to generate energy lies in its continuous availability. Unlike wind or solar energy, which depends on the availability of natural forces (wind and daylight), the production and consumption of biomass can be separated, i.e. biomass can be stored prior to its consumption. Considering the local land quality conditions of the CWDM, this study was limited to the production of lignocellulosic biomass, i.e. trees grown in a short-rotation coppice (SRC) system. Besides their capability of sustaining longer periods of frost or droughts, short-rotation crops such as willow, poplar or eucalyptus have turned out to be the biomass materials with the highest energy potential. Moreover, while intensive biofuel and bioenergy crops such as maize and canola are limited to highly productive land and, thus, compete with conventional agricultural activities for land, short-rotation coppice (SRC) plantations can be established on marginal and degraded land.

As shown in this study, the life-cycle assessment (LCA) approach, originally developed as an environmental assessment tool, can support decision-making by providing environmental performance information in a structured and comprehensive way. It can be understood intuitively as a tool that captures environmental impacts along the entire life cycle (from its 'cradle' to its 'grave') of a product or a service. There is broad agreement in the scientific community that LCA is one of the most effective methods for evaluating the environmental burdens associated with biofuel and bioenergy production. Due to its structured and systematic approach, LCA is well suited for integration with other complementary system assessment methods, such as multi-period budgeting (MPB) and geographic information systems (GIS). These widely recognised and applied methods generate additional performance data covering technical, financial-economic and socio-economic aspects along the bioenergy system's life-cycle.

By providing financial-economic, socio-economic and environmental performance data, the combined use of these assessment methods supports integrated decision-making in both a broad (public) context and a narrow (private) context. In a narrow context, it provides in-depth information for decision-making at an operational level, e.g. in a farming context. In a broad context, the provided information aids public decision-making by illustrating the trade-offs of the different alternatives, as well as the respective opportunity costs when selecting one alternative over another. In the latter case, however, additional support for the decision-making process of identifying the most sustainable solution is required, as the barrier to implementing bioenergy projects in terms of the multiple, and often conflicting objectives, persists. The multi-criteria decision analysis (MCDA) approach can aid decision makers to overcome such a decision-making barrier. It has gained recognition to support decision-making as a tool that organises and synthesises the respective information, which is capable of integrating mixed sets of data (qualitative and quantitative), and which assists the decision maker to place the problem in context and to determine the preferences of the stakeholders involved. In essence, based on a number of defined criteria, the goal of a decision maker is to identify an alternative solution that optimises all the criteria. However, in complex projects like bioenergy assessments, it is impossible to optimise in terms of all the criteria at the same time; therefore, a compromise solution needs to be sought by using subjective judgements of the considered criteria and by combining these as weighted scores to obtain an overall ranking of alternatives. Thus, MCDA aids decision-making processes by integrating objective measurement with value judgement, by making subjectivity explicit, and by managing this subjectivity in a transparent and reproducible manner.

A number of MCDA studies integrating other assessment methods for providing performance data (e.g. LCA) to support decision-making processes concur that environmental, financial- and socio-economic criteria need to be included when seeking to determine the most sustainable energy project for implementation. However, a great deal of them fall short in their application, as they either consider only a single dimension (finance, social or environment) or they take a very limited number of other aspects into account (e.g. only one aspect for each dimension). The immaturity of complementary assessment methods, the data intensity, and the lengthy process of generating the respective information are given as explanations for omitting other sustainability indicators.

In the early stage of the LCA, 37 lignocellulosic bioenergy systems (LBSs) were defined, encompassing different combinations of types of harvesting and primary transport in the SRC plantation, types of pretreatment (comminution, drying, fast pyrolysis) and locations thereof (roadside or landing of the central conversion plant), types of secondary transport from the roadside to the central conversion plant, and types of biomass upgrading and conversion into electricity. Each of these were assessed against a set of 13 key criteria, consisting of five financial-economic viability criteria, three socio-economic potential criteria and five environmental impact criteria. Four so-called biomass procurement areas (BPAs), namely Paarl, Worcester, Ashton and the Rural Cederberge, which differ, *inter alia*, in their biomass productivity (a mean annual increment of 27, 18, 9 and 5 tonnes of fresh biomass respectively), their availability of land and the resulting extent of the procurement area were used to determine the performance of the 37 LBSs in terms of the defined criteria. The quantitative performance data was then, as part of the MCDA process, translated into a standardised common language of relative performance. Taking the stakeholder preferences into account, weights were attached to the considered criteria by means of the analytical hierarchy process (AHP). The 'financial-economic viability' main criterion received a preference of almost 60%, 'socio-economic potential' nearly 25% and 'lowest environmental impact' the remainder of around 16%.

With the results of this study, the first hypothesis was proven to be correct. This hypothesis states that life-cycle assessment and other complementary system assessment methods, including multi-period budgeting and geographic information systems, can be used as structured and comprehensive techniques for the detailed analysis of complex lignocellulosic bioenergy systems, to provide quantitative financial-economic, socio-economic and environmental performance data. The second hypothesis also proved to be correct, as this study confirms the applicability and suitability of multi-criteria decision analysis to aid decision-making processes, such as identifying – by integrating and evaluating the provided performance data – the most sustainable lignocellulosic bioenergy system for the Cape Winelands District Municipality.

The following main facts and principles were derived from developing and implementing the methods employed. These can serve as guidelines for planning and developing sustainability-driven assessments of renewable energy systems in general and lignocellulosic bioenergy systems specifically, taking financial-economic, socio-economic and environmental criteria into consideration:

(i) The outcome of the multi-criteria decision analysis for the introduction of lignocellulosic bioenergy systems (LBSs) in the Cape Winelands District Municipality (CWDM) showed that LBS 26 would be the preferred option in the Paarl and Worcester biomass procurement areas, and the next-best option, after LBS 13, in the Ashton and Rural Cederberge BPAs. However, LBS 26 would be preferred across all areas of the CWDM if the prerequisite of financial-economic viability were to be taken into consideration (i.e. if the alternative is not profitable, private investors will not be interested in investing in this particular alternative), despite various levels of productivity. LBS 26 comprises a feller-buncher for harvesting, a forwarder for the primary transportation of the biomass to the roadside, where the biomass is comminuted and then transported in containers to the central conversion site. For its conversion into electricity, the South African-designed and -made System Johansson Gas (SJG) producer, by Carbo Consult & Engineering (Pty) Ltd, was adopted. This system is based on parallel series of integrated gasifier-gas-turbine systems. The environmental impact and socio-economic potential of LBS 26 would be so similar across the four areas as to not cause a significant deviation from the financial-economical-dominated ranking.

(ii) LBS 26 is expected to be profitable in all biomass procurement areas. A comparison of the four BPAs shows that the greatest 'financial-economic potential' can be expected for the Worcester area, since it has relatively the best ratio between biomass productivity and land cost. Therefore, it can be concluded, that it will not necessarily be the most productive land that will give the highest returns, but rather the area with the best balance between land productivity and land price, thereby recognising the equalising effect of the land market.

(iii) Using the current South African energy mix as a reference system (more than 90% of South Africa's electricity generation is based on fossil fuels such as coal or oil), all investigated lignocellulosic bioenergy systems are expected to perform better in terms of the environmental impact criteria. In terms of global warming potential, which is expressed in tonnes of carbon dioxide-equivalent emitted, even the worst performing LBS reaches levels of only eight percent of the SA energy mix. Only in terms of eutrophication potential do the LBSs' results exhibit similar outcomes to the current SA energy mix, which can be explained by the negative impact of applying fertilisers. Using the Worcester biomass procurement area as an example, from an environmental point of view, LBS 26 reaches abiotic depletion levels of 14% of those of the current South African energy mix, a global warming potential of 4%, an acidification and eutrophication potential of 16% and 92% respectively, and a photochemical ozone creation potential of 19%. Thus, generating electricity with a lignocellulosic bioenergy system represents a sustainable alternative to the current energy mix, contributing positively to the environmental balance of South Africa as a whole.

(iv) Due to a lack of data for the SA energy mix, comparisons in terms of financial-economic and socio-economic performance were not possible. The national energy supplier, ESKOM, has various electricity tariffs, depending on types of consumers and their locations. Furthermore, ESKOM does not disclose detailed information on the employment it provides. Hence, comparisons with the assessed bioenergy systems were not possible. Nevertheless, ESKOM's current electricity tariff of around R0.80/kWh for the private consumer in the Stellenbosch area is significantly lower than the R1.06/kWh at which ESKOM is supposed to purchase electricity produced from solid biomass, as proposed by the national energy regulator of South Africa (NERSA). However, increases in electricity tariffs in recent and forthcoming years are expected to improve the competitiveness of renewable energy systems in general. Income from trading certified emission reduction (CER) certificates can further improve the profitability of lignocellulosic bioenergy systems.

(v) In contrast with the current energy mix of South Africa, this study of lignocellulosic bioenergy systems incorporates a variety of socio-economic and environmental considerations. MCDA was used to translate the generated performance data into a standardised common language of relative performance. This stands in contrast to single goal optimisation, and approaches using 'unifying units' to offset poor performances in terms of one criterion against another criterion. This latter approach is adopted in cost-benefit analyses (CBA) using monetary values assigned to parameters, allowing for substitution and comparability between criteria. However, environmental impacts such as 'eutrophication potential' (EP, expressed as t Phosphate-equivalent) or 'Photochemical ozone creation potential' (POCP, expressed as t Ethane-equivalent) cannot be expressed in monetary terms, and therefore, cannot be taken into account sufficiently when making decisions, giving rise to typical externalities. MCDA does not internalise these considerations by means of valuation methods expressing them in monetary terms on a cardinal scale, but accommodates them via scores and weights using ordinal scales. Hence, MCDA avoids the classical problem of not being able to internalise non-monetary considerations via monetarisation.

(vi) As shown in this study, GIS can be a useful tool for providing a basis for life-cycle assessment, by accommodating resource quality and accessibility considerations. By means of GIS, around 175 000 hectares out of a total of 2.3 million hectares in the CWDM were identified, in a land availability assessment, as being suitable for producing lignocellulosic biomass in an SRC plantation system. Using available spatial information on land-use cover and precipitation patterns, amongst others, GIS helped to identify the extent and location of potential production areas, by excluding unsuitable areas such as urban developments, intensive agricultural/arable land, and environmentally and socially sensitive areas (e.g. biodiversity hotspots and buffer zones along waterbodies).

(vii) In excluding environmentally and socially sensitive areas, GIS also aided the decision-making process, by limiting the number of criteria involved. Environmental concerns such as the impact on biodiversity or on water balance, or socio-economic concerns such as the competition between food and biomass production are often reasons for heated discussions, due to the difficulties in measuring these impacts, and are, therefore, difficult to quantify. Within the LCA approach, no recognised and established life-cycle impact assessment method covering these environmental or social-economic concerns is available for assessing bioenergy projects. Thus, GIS can help to minimise these impacts, by using spatial data to exclude sensitive areas.

(viii) During the transport modelling assessment, GIS also helped to identify potential bioenergy conversion sites, taking various proximity aspects into consideration (e.g. proximity to electricity substations and major grid lines, to minimise feed-in costs; proximity to external customers, to whom potential excess heat/thermal energy could be sold; proximity to the road network, as the accessibility of the conversion sites affects feedstock transport efficiency and obviates the costs of additional infrastructure). This further highlighted the practicality and multi-functionality of GIS in aiding the assessment of renewable bioenergy systems.

(ix) Changes in land use can potentially alter carbon stocks, by releasing or sequestering soil and vegetation carbon – an issue often neglected in the assessment of bioenergy projects. In the context of the CWDM, the introduction of SRC plantations will result in an increase in carbon stock, particularly when substituting rain-fed intensive and extensive farmlands. The only exception is expected for irrigated, perennial crops in the drier parts of the CWDM. The correlation between biomass productivity and carbon sequestration capacity becomes apparent when comparing the biomass procurement areas against each other. SRC plantations in the Paarl BPA will nearly double the capacity of those in the low productivity Rural Cederberge BPA to store carbon. Hence, the results of this study confirm that primary productivity is a function of mean annual precipitation and temperature, as well as of organic matter inputs to the top soil tending to be greater in mesic than arid regions. Furthermore, they confirm that C storage capacity increases with an increase in lignocellulosic biomass.

(x) One of the core elements of a life-cycle assessment of a product or a system is the functional unit, which provides a reference against which the input and output process data are normalised and a basis on which to present the final results. The functional unit used in this study is a dual time-product measurement, in terms of which the burdens calculated for an average year's operation are normalised to the total electrical power of a 5 megawatt system produced per year: an annual electricity generation of 39 600 megawatt hours (MWh). For the financial-economic and the socio-economic assessment, however, a longer time boundary based on accounting principles was used: an economic business cycle of 20 years for the biomass upgrading and bioenergy conversion units, plus one rotation length to ensure the sustainable feedstock supply to the conversion plant, i.e. 25, 27, 30 and 35 years for the Paarl, Worcester, Ashton and Rural Cederberge BPAs respectively. This was done to capture the effects in terms of costs and profitability over the entire financial-economic life-cycle. The use of different functional units in this study is aimed at providing sufficient insight and a good understanding of the impacts and performances of the alternatives. MCDA provides the means to integrate these different 'languages', by translating them into a standardised common language of relative performance.

(xi) One of the reasons for LBS 26 being ranked top can be given as the overall conversion efficiency (OCE) of its biomass upgrading and bioenergy conversion system (BCS). In absolute terms, LBS 26 requires 52 937 tonnes of fresh woody biomass annually to ensure continuous electricity generation. LBS 24, which was ranked last across all biomass procurement areas, requires 87 272 tonnes per year to reach the same electrical output, around 65% more than LBS 26. This translates to an OCE of around 25% for LBS 26 and around 16% for LBS 24. Thus, the greater the OCE, the less bioenergy feedstock is required, resulting in fewer upstream activities and less land being required for biomass production. This makes the OCE the most decisive factor for the success of an entire bioenergy value chain, whether it be of a financial-economic, socio-economic or environmental nature. In terms of environmental impact, a greater OCE is desired, resulting in lower total emissions and, therefore, in lower impacts for each life-cycle impact category. Similarly, for the financial-economic viability, a greater OCE results in lower costs, both in terms of capital and operating expenditure, as well as in higher internal rates of return on the capital invested. The opposite picture may emerge for the socio-economic criteria, expressed in employment creation potential. The lower the OCE, the greater the employment creation potential, particularly for the unskilled and semi-skilled income categories, taking South African conditions into consideration. This relationship illustrates another important aspect, namely that environmental and financial-economic viability criteria are not necessarily contradictive and that the maximisation of one of them also has positive effects in terms of the other. The maximisation of direct employment as a socio-economic indicator, however, has a negative effect on financial-economic viability and environmental impact.

(xii) A comparison of the rankings of the lignocellulosic bioenergy systems shows that most of the top-ten-ranked alternatives use the same biomass upgrading and bioenergy conversion system (BCS) as used by LBS 26. The next group in the rankings consists in most instances of alternatives comprising direct combustion integrated boiler-steam-turbine systems. In contrast, alternatives comprising the fast-pyrolysis technology as part of the BCS can be found at the lower end of the rankings. Therefore, based on the BCS technologies considered in this study, it could be said that with greater maturity of the BCSs used, lower capital costs and greater conversion efficiencies can be expected. While direct biomass combustion and gasification technologies are relatively well established and have been proven by their reliability, resulting in relatively lower capital costs and greater conversion efficiencies, the relatively immature fast-pyrolysis technologies used for biomass upgrading have not proven viable. This has even been the case in remote areas where the densification of the original feedstock by means of fast-pyrolysis into more valuable energy carrier bio-oil and bio-char, aimed at reducing secondary transport costs, was expected to play a potential role. The high capital and operational costs, as well as the relatively low OCE currently do not justify their application in the context of bio-electricity generation. However, this may change in future, when, for instance, the application of bio-char to soil as a means for carbon sequestration is accepted for the cleaner development mechanism (CDM), i.e. as a scheme for carbon credit trading, which could provide significant additional income and, thus, could make such an operation viable.

(xiii) Another important consideration for the assessment of bioenergy systems is the efficiency of the harvesting system, which has an effect similar to the OCE. In the context of the CWDM, motor-manual harvesting has been found to be the most beneficial in terms of the creation of employment in the unskilled and semi-skilled income categories, while relatively greater harvesting efficiency is reached using the modified self-propelled forage harvester, involving felling and comminution of the trees occurring in a single operation, and resulting in relatively low environmental impacts and low production costs, in turn resulting in a positive impact on overall profitability. This harvesting system, however, is also characterised by relatively low direct employment creation potential. Thus, the greater the degree of mechanisation and automation of the harvesting system, the lower the environmental impact and the higher the cost-effectiveness and profitability, but also the lower the socio-economic benefits in terms of employment creation potential.

(xiv) Various discussions and research projects in South Africa have also considered the use of invasive alien plant species (AIPs) to generate bioenergy. While no production costs are assumed for AIPs, the procurement costs are expected to be comparatively high, as AIPs are distributed over wide areas and, in many cases, in difficult terrain. The methods applied in this study provide a sound approach for evaluating the financial-economic, socio-economic and environmental performances, not only of SRC plantation-based bioenergy systems but also of other bioenergy options. In the case of AIPs, for instance, they can help decision makers in their decision-making processes, by providing accurate and reliable data to weigh up different aspects, such as production costs against procurement costs.

8.2 Summary

Chapter 1 serves as a general introduction to the study, giving background information on the global and local issues driving renewable energies coming to the fore, and on the need for more sustainability-driven approaches to assessing energy system projects.

Finite reserves, and the rapidly increasing demand for energy sources, expressed by the uncertainty surrounding oil prices, the need for security and diversification of energy supplies and the inability of the environment to maintain its sink function (maintaining its assimilative capacity without unacceptable degradation of its future waste absorptive capacity or other important services) are some of the major social, political and economic challenges that have prompted the international community to investigate alternative energy sources. This has resulted in a new energy paradigm, from fossil to renewable energy sources, including hydro, solar, wind and biomass-based energy systems, and coincides with a demand for new ways of measuring the viability of energy systems. In the past, financial and technical considerations were the main drivers of selecting a suitable energy carrier, leading to fossil fuels as the preferred choice. The introduction of renewable energies resulted in a more sustainability-driven approach, meaning the implementation of alternatives that are technically efficient, economically viable, environmentally sound and socially acceptable. This, however, necessitates more sophisticated measurements in terms of a wider range of criteria, covering not only financial-economic, but also environmental and socio-economic aspects.

The life-cycle assessment (LCA) approach, originally developed as an environmental assessment tool, has gained recognition, as it provides environmental performance information in a structured and comprehensive way, to support decision-making in both the private and public sectors. LCA can be understood intuitively as a tool that captures the environmental impacts along the entire life cycle of a product or a service (from its 'cradle' to its 'grave'). It is regarded as one of the best methodologies for evaluating the environmental burdens of renewable energy systems. Further, LCA is believed to be well suited for integration with other, complementary assessment methods, such as multi-period budgeting (MPB) and geographic information systems (GIS). While LCA provides environmental performance data, these widely recognised and applied methods generate additional performance data, covering technical, financial-economic and socio-economic aspects along the product's life cycle. However, the main problem in finding the most viable/most sustainable alternative in a decision environment with multiple, and often conflicting objectives persists. Multi-criteria decision analysis (MCDA) has come to the fore as a method that is capable of aiding decision-making by organising and synthesising the respective performance data, by integrating mixed sets of data (qualitative and quantitative), and by assisting the decision maker to place the problem in context and to determine the preferences of the stakeholders involved.

Public and private decision makers of the Cape Winelands District Municipality (CWDM) in the Western Cape, South Africa, are confronted with such a decision-making problem, as they seek to implement viable/sustainable renewable energy systems in the CWDM. The resulting complexity, however, constitutes a major barrier to their implementation, as much information of a complex and conflicting nature needs to be processed. Adopting a case study approach, this dissertation aims to illustrate how to aid such a decision-making process by providing quantitative performance data and by integrating various considerations using the above-mentioned research methods.

Chapter 2 provides the reader with additional background information on the study area and the resource baseline, as well as with a definition of the biomass and its properties considered as feedstock for generating bioenergy. Great variations in topology, climate and soil conditions characterise the 2.23 million hectares of the CWDM, which is located in the centre of the Western Cape Province and is shaped by a Mediterranean climate and a historically strong deterministic water supply (winter rainfall) from April to August. The south-western part of the CWDM is mainly frost free, but some areas towards the interior regularly experience periods of frost during winter and droughts during summer. One of the main concerns for public decision makers in the CWDM is the unemployment rate. Almost 21% in the CWDM (mostly in the unskilled to semi-skilled category) are unemployed, creating a variety of socio-economic problems.

Biomass is considered to be one of the most promising alternatives to conventional fuels, as it is the only renewable source of fixed carbon, which can be converted to liquid, solid and gaseous fuels, in addition to heat and power. Bioenergy has an almost closed CO_2 cycle, as the combustion of biomass releases the same amount of CO_2 as was captured during its growth: only in the production stages are additional greenhouse gases (GHG) emitted by using external fossil fuel inputs to produce and harvest the feedstock, in processing and handling the biomass, in transporting the feedstock and in bioenergy plant operation. Some short-rotation coppice (SRC) crops such as willow, poplar, eucalyptus and other fast-growing tree species are not only frost and drought resistant, but have also turned out to be the biomass materials with the highest energy potential.

Based on a land availability assessment, around 175 000 hectares were identified as being suitable for the production of energy wood in a short-rotation coppice system. With the aim of limiting the impact on the environment (e.g. biodiversity) and to avoid competition between food and biomass production, GIS was used to exclude non-suitable areas, most importantly areas with water limitations and ecologically sensitive areas, thereby decreasing the number of considerations to be handled during the multi-criteria decision analysis discussed further on. The biomass availability assessment indicated that about 1.4 million tons of fresh biomass lignocellulosic biomass could be supplied annually, assuming medium productivity. In general, indigenous species (e.g. *Acacia karoo*) are expected to produce higher yields in the interior, low production areas in the north-east of the CWDM, while exotic species (e.g. *Eucalyptus cladocalyx*) grow better in areas with higher production potential compared with indigenous species.

The general characteristics and the chemical composition of suitable trees grown in an SRC system are important considerations for the assessment of bioenergy systems, influencing the various production stages. Besides the inherent calorific value, the moisture content of the bioenergy feedstock plays a particularly important role, as it affects, *inter alia*, handling, transport costs, and conversion efficiency.

Aimed at familiarising the reader, Chapter 3 provides a comprehensive description and discussion of the methods applied in this study, including the origin, structure, and a discussion of recent applications of each method in the fields of agriculture, forestry and bioenergy. This is followed by a discussion of recent studies dealing with the combined use of both methods, highlighting the need for the expansion of existing research methods aimed at dealing with multi-criteria decision contexts.

In recent years, an increasing number of LCA studies have dealt with environmental impacts in the primary sector, including conventional agricultural and forestry activities, as well as energy crop production and whole biofuel/bioenergy systems, often aimed at comparing the environmental impacts of a certain system to the environmental impacts of a reference system. In the case of bioenergy, this means that the selected bioenergy system is compared with a fossil reference system. In general, an LCA consists of four phases, namely goal and scope definition, inventory analysis, impact assessment, and interpretation of the results. Various types of LCA exist, but in general, a distinction is made between two types, namely accounting and change-oriented LCAs, with the former being comparative and retrospective (e.g. eco-labelling). Identification of the most sustainable bioenergy system can be assigned to the latter, which is comparative and prospective, and aimed at supporting decision-making.

Similarly, with a heightened awareness of a more sustainable approach in decision-making in the public and private sector, MCDA has received increased attention in recent years, including for selecting the most viable agricultural, forestry and renewable energy systems. MCDA, which can be defined as ‘formal approach that seeks to take explicit account of multiple criteria in helping individuals and groups explore decisions that matter’, stands in contrast to single goal optimisation, and approaches using ‘unifying units’ to offset poor performances in terms of one criterion by good performances in terms of another criterion. The latter approach is adopted in cost-benefit analyses using monetary values assigned to parameters, allowing for the substitution and comparability of criteria. MCDA in its use of interval scaling and weights, and in its focus on relative trade-offs within each dimension, avoids many of the problems associated with monetary evaluation techniques, while still permitting the assessment of potential trade-offs between criteria. Various

MCDA methods exist, generally classified as value measurement models, goal aspiration and reverence-level models, and outranking models. In essence, the process of MCDA involves a number of defined criteria against which viable management alternatives are assessed in terms of scores. The goal of the decision maker is to identify an alternative solution that optimises all the criteria. However, the concept of an optimum does not exist in a multi-criteria framework; thus, a compromise solution needs to be actively sought by using subjective judgements of the considered criteria and by combining these as weighted scores to obtain an overall ranking of the alternatives.

A variety of studies discuss the combined use of LCA and MCDA. However, while a variety of studies concur that environmental, financial- and socio-economic criteria need to be considered when seeking the most sustainable alternative, most of them fall short in their application, as they consider either only environmental aspects (in most instances solely LCA-based criteria) or they take a very limited number of financial and social aspects into account (e.g. only one for each aspect). The early development of complementary assessment methods, the data intensity, and the lengthy process of generating the respective information are given as explanations for omitting other sustainability indicators.

This study provides a more comprehensive, more sustainability-driven approach in determining the most viable lignocellulosic bioenergy system for the CWDM, using LCA and other complementary assessment methods, including MPB and GIS, to provide financial-economic, socio-economic and environmental performance data. The analytical hierarchy process (AHP) – one of the commonly applied and accepted MCDA approaches, characterised by its simplicity, and possessing the natural appeal of expressing relative importance by means of pairwise comparisons in ratio terms – was applied to integrate and evaluate the generated performance data, resulting in an overall ranking of the alternatives.

Along the lines of the LCA method, the first LCA phase (goal and scope definition) is covered in Chapter 4. This sets the foundation for this study by defining its goal and scope and by specifying the functional unit and the different dimensions of systems boundaries. The latter included the technical system boundaries, resulting in a set of 37 lignocellulosic bioenergy systems (LBSs), which are characterised by different combinations: type of harvesting and primary transport in the SRC plantation (the latter is also referred to as forwarding or extraction), type of pretreatment (comminution, drying, fast pyrolysis) and location thereof (roadside or landing of the central conversion plant, type of secondary transport from the roadside to the central conversion site, and type of biomass upgrading and conversion into electricity. For each production phase of the life cycle, general background information on trends and state-of-the-art technologies and systems was provided. The functional unit was defined as 'burdens calculated for an average year's operation normalised to the electrical power produced per year', i.e. the electricity generated annually by a 5-MW system over 330 days of full production. Four potential sites/biomass procurement areas (BPAs) within the CWDM were selected as geographical boundaries (Paarl, Worcester, Ashton and Rural Cederberge), based on their different site conditions and their different biomass productivity rates (relatively high, medium, low, very low respectively), which were estimated by experts taking available climate data into consideration. Other boundaries in relation to the natural system were specified by taking land-use change-related carbon stock changes for each of the BPAs into account.

This is followed by Chapter 5, which entails a detailed life-cycle inventory (LCI) for each of the 37 lignocellulosic bioenergy systems. Information was gathered about all process-related inputs and outputs of the studied systems. For each process, qualitative and quantitative data, i.e. relating to machinery and equipment, was assumed, and the related productivity was specified, not only in terms of environmental input and output flows, which are typical for an LCI, but also by considering related financial-economic (capital and operational expenditures, income from selling electricity and related by-products such as thermal energy, bio-char or carbon credits) as well as socio-economic (direct employment creation potential) data. Various sources including the GaBi 4.4 database, the literature, and industrial data were used to calculate the environmental impacts and financial-economic performance, assuming best operating practices for each process. Each of the lignocellulosic bioenergy systems consist of five production phases, namely (i) primary production of biomass in short-rotation coppice (SRC) plantations; (ii) harvesting and primary transportation of the biomass from in-field to the roadside; (iii) pretreatment of the biomass, including comminution, drying and mobile fast pyrolysis; (iv) secondary transport of the bioenergy feedstock from the roadside to a central conversion plant; and (v) biomass upgrading and conversion into electricity.

The first production phase, primary biomass production, is common to all alternatives and takes all the activities and processes in the establishment and maintenance of the SRC plantations into account. The second production phase, harvesting and primary transport, comprises five harvesting system modules, including three different harvesting technologies and three types of primary transportation. The harvesting technologies modelled are motor-manual machinery, mechanised forestry machinery, and modified agricultural machinery. A forwarder fitted with a crane; a tractor-pole-trailer combination loaded and unloaded, either manually or with a three-wheeler loader; and a tractor-container-trailer combination were assumed for the primary transportation. The third production phase, pretreatment of the biomass, entailed three types of activities, namely comminution, drying and mobile fast pyrolysis. Depending on the harvesting system applied, two locations for comminution were proposed, i.e. mobile comminution at the roadside and stationary comminution at the landing of the central conversion plant. Similarly, both the location of the stored biomass and the shape of the biomass (comminuted or uncomminuted) depend on the harvesting systems applied. In the case of four of the harvesting systems, uncomminuted biomass is stored in-field to air-dry for several weeks until the biomass has reached moisture content levels of around 40% (on a dry-matter basis). Once this level has been reached, the biomass is forwarded to the roadside for further processing. In the case of the remaining harvesting system, the trees are felled and comminuted in a single process, resulting in wood chips with moisture content levels of around 80% (dry basis). However, exhaust heat from the respective conversion system is used to reach the moisture content levels required for the upgrading and conversion process; no additional energy will be required to reach the stipulated moisture content levels of the bioenergy feedstock. Hence, no additional costs and emissions arise from the active drying process. Some of the alternatives use mobile fast pyrolysis, a process whereby the biomass is degraded in the absence of an oxidising agent, i.e. the volatile components of a solid carbonaceous feedstock are vaporised in primary reactions by heating, leaving a residue consisting of bio-char and ash. Pyrolysis always produces a gas vapour that can be collected as a liquid and as a solid char. Fast pyrolysis processes are designed and operated to maximise the liquid fraction by up to 75wt.% on a dry-biomass-feed basis. Thus, although fast pyrolysis can be understood as some form of pretreatment of the biomass, it also represents one of the possible pathways for upgrading low-bulk-density biomass into densified, more homogeneous energy carriers (bio-oil and bio-char).

The fourth production phase encompasses the secondary transport of the bioenergy feedstock from the roadside to a central conversion plant. Uncomminuted biomass is assumed to be transported with a truck-pole-trailer combination, comminuted biomass and bio-char with a truck-container-trailer combination, and bio-oil from a mobile fast pyrolysis system by a dedicated truck-tanker-trailer combination. Only when transporting comminuted biomass from whole trees or bio-oil is the payload capacity limited by the volume; in all other instances, mass is the limiting factor. Various other factors had to be considered to determine the total mass transport rate, including fixed and variable time requirements. Fixed time includes the time for all non-travelling activities, i.e. loading and securing of the load prior to travelling, and once the destination has been reached, the clearing of the load (unloading and weighing prior to and after unloading). The calculations of the variable time requirements for secondary transport depend on a variety of considerations. The average transport distance, for instance, is a function of the supply and demand for bioenergy feedstock. The supply depends, *inter alia*, on the suitability of land for biomass production, the willingness of landowners to participate by offering their land for lignocellulosic biomass production, and the productivity rate of the respective areas. The demand component is driven mainly by the conversion efficiency of the respective bioenergy system, but also by feedstock losses during the procurement and pretreatment of the feedstock. The above-mentioned land and biomass availability assessment served as basis for a transport optimisation model using GIS and LINGO, where the weight-average transport distance in terms of each lignocellulosic bioenergy system and each biomass procurement area were calculated. In turn, this was used to determine the number of truck configurations required, taking the total number of shuttle trips for each truck configuration and the total transport time (variable and fixed) into account.

Five configurations of bioenergy conversion systems (BCS) were assumed for the fifth production phase. The first bioenergy conversion system (BCS I) entails an integrated steam-turbine system, where the biomass at a maximum 20% moisture content (dry basis) is combusted to generate steam, which is then used in a steam turbine to generate electricity. The same moisture content (MC) is required for BCS II, an integrated gasifier-gas-turbine system, where the biomass is upgraded to bio-gas, which in turn, is fed into a gas turbine. BCS III consists of a stationary fast-pyrolysis plant converting biomass (10% MC) into bio-oil and bio-char. The upgraded products are then fed into an integrated boiler-steam-turbine system to generate electricity. An integrated steam-turbine system is also assumed for BCS IV, also using bio-oil and bio-char that is produced in a mobile fast-pyrolysis system at the roadside, close to the primary biomass production sites. The last bioenergy conversion system (BCS V) also encompasses mobile fast-pyrolysis systems, but differs in the final conversion step, where only bio-oil is used to generate electricity, by directly injecting the liquid into a gas turbine. Also transported to a central facility, the bio-char by-product is assumed to be sold to the fertilising industry, which uses it as an additive for soils. To some extent, this effectively works as a way of capturing and storing carbon.

The first two bioenergy conversion systems are based on well-established commercial options for the production of electricity from wood, resulting in relatively good conversion efficiencies and low capital and operational costs. Only BCS II is South African-designed and -made, while all other systems are either from Europe or the United States, creating some uncertainty in terms of exchange rate and production capacities. Some of the data used is based on the conversion systems working at production capacities that differ from the stipulated $5MW_{el}$. In these instances, the so-called six-tenth factor rule was used to estimate the capital cost of the conversion plants. For each of the BCSs, an economic lifetime expectancy of 20 years was assumed. An electricity tariff of R1.06 per kilowatt hour, for which the generated electricity is sold, was based on the renewable energy feed-in tariff (REFIT), as stipulated by the national energy regulator of South Africa (NERSA). For the first three biomass procurement areas, it was assumed that the excess heat/thermal energy is sold to industrial consumers for heating/cooling purposes at a rate of R0.15/kWh_{th}. Additional income was assumed for selling certified emission reduction (CER) certificates (also called carbon credits) into the carbon market at a rate of R100/t of CO_2 emissions avoided, taking the current South African energy mix into account.

Quantifying and determining the emissions caused by the conversion systems appeared to be particularly challenging, since no actual data using the assumed feedstock was available. In order to overcome this problem, a simplified approach was used, applying the so-called thermo-chemical equilibrium and theoretical or stoichiometric oxygen or air requirement, which assumes the complete combustion of the feedstock. The emissions are based on the amount of oxidant that is just sufficient to burn the carbon, hydrogen, and sulphur in a fuel to carbon dioxide, carbon monoxide, water vapour and sulphur dioxide. Thus, the gas ratios applied in this study represent a lower limit of emissions, but give some indication of the emissions to be expected. Sophisticated software packages could have been used to calculate more accurate emission estimates, requiring additional information on enthalpy and combustion conditions, but this would have entailed a study in itself, requiring going beyond the scope of this study. Potential water consumption was not included in the LCA, as closed water cycles were assumed for the conversion systems. The recirculation of ash for fertilisation purposes, the only 'waste' in lignocellulosic bioenergy systems, was considered, but since ash recirculation systems are not commercially available, it was assumed to be used for landfill or for construction material.

Chapter 6 entails the third phase of the life-cycle assessment, the life-cycle impact assessment (LCIA). The purpose of the LCIA is to better understand the environmental significance of a product system's life cycle by assessing its inventory results. This was achieved by translating the environmental loads from the inventory results of the 37 lignocellulosic bioenergy systems for each of the biomass procurement areas into environmental impacts, using the so-called CML 2001 method (normalisation factors from November 2009). CML 2001 is a collection of impact assessment methods that restricts quantitative modelling to the relatively early stages in the cause-effect chain, to limit uncertainties and to group LCI results into midpoint categories, according to themes. The environmental impact categories taken into account were abiotic depletion potential (ADP, measured in gigajoules), acidification potential (AP, t SO_2-equivalent), eutrophication potential (EP, t phosphate-equivalent), global warming potential ($GWP_{100years}$, t CO_2-equivalent), and photochemical ozone creation potential (POCP, t ethene-equivalent). The toxicity impact categories (human toxicity potential, as well as terrestrial, freshwater aquatic and marine aquatic eco-toxicity potentials) were not included in this study, due to a lack of consistency in the field of hazardous substances and heavy metals, as well as a lack of inventory data for emissions, creating data gaps, potentially resulting in incorrect conclusions stemming from inconsistent data. Other important environmental impact assessment methods not included in the LCIA, such as the *biodiversity intactness index* and the *water footprint* were also discussed, but were not included in this study, since they are not included in the commonly accepted LCIA methods. In addition, both environmental impacts have been dealt with a priori in the land availability assessment, by means of GIS.

Furthermore, using the LCA framework as a guideline, a set of financial-economic and socio-economic criteria was defined, against which the LBSs were assessed. By means of multi-period budgeting (MPB), financial-economic data was translated into key parameters describing the profitability and cost performance of each LBS, making them more comparable. Internal rate of return (IRR), expressed as a percentage, was used as a profitability indicator. Four cost indicators were considered important in terms of risk of investment: capital and operational costs of technology for biomass upgrading and conversion ($CAPEX_{conv.}$ and $OPEX_{conv.}$). The establishment of a bioenergy conversion system represents a capital-intensive venture, characterised by significant risks (e.g. sufficient supply of feedstock, continuity of production, reliability of the conversion technology and all ancillary systems, and a guaranteed market for the products produced) that are carried by either a single or a few private investors, a public investor, or a joint venture between public and private sectors. Costs other than conversion technology ($CAPEX_{other}$ and $OPEX_{other}$) include all expenses along the value chain prior to biomass upgrading and bioenergy conversion, i.e. from the land valuation, primary production of biomass, harvesting, forwarding, comminution and secondary transport, amongst others. In contrast with the costs of the conversion systems, the costs occurring during the other production phases are carried by a variety of investors, such as land owners and entrepreneurs (small business owners, contractors, etc.).

'Direct employment creation potential', subdivided into three income categories, was used as the socio-economic indicator, based on the productivity data of each production phase used in the MPB and LCA models. DECP I comprises the number of jobs created for unskilled to semi-skilled labourers (earning an income of less than R8 000 per month), including farm and forest workers, chainsaw, tractor, three-wheeler loader, and conversion plant operators, as well as assistants to truck drivers during secondary transportation. DECP II (earning an income from R8 000-R24 000 per month) includes all skilled labourers, such as operators of combine harvesters, feller-bunchers, forwarders, service technicians for the stationary comminution units, and truck drivers. Highly skilled labourers earning a monthly income of more than R24 000, such as engineers and managers for the conversion plant as well as for the supply chain, are aggregated in the category DECP III. Similar to the environmental impacts biodiversity and water balance, food security, another socio-economic impact was also briefly discussed.

The main driver for each criterion, whether it be of an environmental, financial-economic or socio-economic nature, is the overall conversion efficiency (OCE) of the biomass upgrading and bioenergy conversion system. The greater the OCE, the less biomass is required, resulting in fewer upstream activities and less land required for biomass production. In terms of the environmental impact of the lignocellulosic bioenergy systems, a greater OCE is desired, resulting in lower total emissions and, therefore, in lower impacts for each life-cycle impact category. Similarly, for the financial-economic viability of the LBSs, a greater OCE results in lower costs, both in terms of capital and operating expenditure, as well as in higher internal rates of return on the capital invested; the lower the OCE, the greater the direct employment creation potential, particularly for the unskilled to semi-skilled income category. Another important driver is the efficiency of the harvesting system, which has a similar effect to the OCE. The greater the degree of mechanisation and automation, the lower the environmental impact and the higher the cost-effectiveness and profitability, but also the lower the direct employment creation potential.

In continuing the LCA approach, Chapter 7 encompasses the fourth LCA phase, the interpretation of the results using the multi-criteria decision analysis (MCDA) method. As illustrated in the previous chapter, the complexity of bioenergy systems constitutes a major barrier to the implementation of bioenergy systems, and hence the decision-making problem was highlighted by the trade-offs between the defined LBS alternatives. Aimed at identifying the most sustainable lignocellulosic bioenergy system, the analytical hierarchy process (AHP), one of the commonly applied MCDA approaches, was applied to support decision makers in the CWDM in their attempt to overcome this decision-making barrier, by organising and synthesising the respective information, by integrating mixed sets of data, and by assisting decision makers to place the problem in context and to determine the preferences of the potential stakeholders involved.

The initial steps of the AHP included the development of a hierarchy of criteria (criteria value tree) and the translation and normalisation of the performance data provided in the previous chapter into a standardised common language of relative performance, i.e. into so-called scores. The aggregation of these scores for each LBS resulted in a ranking of the alternatives, with each criterion being equally important. Consequently, the decision-making problem persisted, as the conflicting nature of some of the criteria, the differing viewpoints of potential stakeholders, and the resulting trade-offs were not considered in this phase of the MCDA, requiring an additional phase in which the stakeholder preferences were taken into consideration, by attaching weights to the considered criteria. Thus, aimed at providing insight, a task team of experts, reflecting the broad section of potential stakeholders, was introduced during a workshop to the decision-making problem at hand, including the alternatives and their respective performances in terms of the predefined criteria. The experts were then requested to express the relative preferences for the criteria by means of pairwise comparisons using the AHP-based ‘Expert Choice’ software. No serious conflicts of opinion between the participants were recorded during the discussions and the weighting procedure, resulting in consensus on a set of weights, where the main criterion ‘financial-economic viability’ received a preference of almost 60%, ‘socio-economic potential’, nearly 25% and ‘lowest environmental impact’, the remainder of almost 16%. The most important sub-criteria are ‘best IRR’ and ‘direct employment creation potential (DECP) I’, with cumulative weights of around 43% and 18% respectively.

The aggregation of the weighted scores into a single indicator allowed a ranking of the lignocellulosic bioenergy systems (LBS), placing LBS 26 at the top in biomass procurement areas (BPAs) I and II and second in BPAs III and IV. Around 73-74% of its aggregated, weighted score is derived from its ‘financial-economic viability’, around 8-9% from its ‘socio-economic potential’ and 18-19% from its ‘lowest environmental impact’. Similar profiles to that of LBS 26 are shown for most of the top-ten-ranked alternatives across all biomass procurement areas. With few exceptions, all encompass biomass upgrading and bioenergy conversion system (BCS) II, namely a parallel series of integrated 450Nm^3/h gasifier-gas-turbine systems. Compared with the other bioenergy conversion systems, BCS II is characterised by relatively low capital and operating costs, as well as by good conversion efficiencies. This again highlights the importance of the overall conversion efficiency, as it also has an effect on all upstream activities, with less biomass and, thus, less land being required, resulting in fewer upstream activities and, therefore, in lower operational and capital costs, including for machinery and land.

In contrast, the relatively poor overall conversion efficiency as well as the relatively high capital and operational costs of the conversion system are the main reasons why in commercial terms the relatively immature pyrolysis technology is currently not a viable option as part of a bio-electricity generating system. Particularly, alternatives deploying bioenergy conversion system III (a centralised, stationary fast-pyrolysis plant for biomass upgrading into bio-oil and bio-char, integrated with a boiler-steam-turbine system) showed poor results and were at the bottom of the ranking across all biomass procurement areas. Similar reasons can be given for alternatives deploying bioenergy conversion systems IV and V, which both encompass mobile fast-pyrolysis units for biomass upgrading. The only exception is the bioenergy conversion system V-driven LBS 13, which is ranked top in biomass procurement areas III and IV. Nearly 60% of LBS 13's aggregated, weighted score is contributed by its socio-economic performance, with the remainder being equally contributed by its financial-economic and environmental performance. LBS 13's relatively low harvesting and conversion efficiency causes such a significantly greater demand in terms of human capital, particularly in the low income category, that its aggregated, weighted score is slightly greater than the second-ranked LBS 26. However, the final decision maker may still select LBS 26, despite the fact that the ranking of BPAs III and IV gives preference to LBS 13, following the prerequisite of financial-economic viability, i.e. if the alternative is not profitable, private investors will not be interested in investing in this particular alternative. In both areas, LBS 13 is expected to generate a negative net present value.

Two aspects contribute to a different outcome for BPAs III and IV, namely (i) the relatively lower biomass productivity, resulting in more land being required to ensure sufficient biomass feedstock supply and, thus, in more material, machinery and human capital being required, and (ii) the relatively lower land value, being one of the main cost factors, resulting in a lower impact in terms of costs on the financial-economic viability, i.e. the tendency to select alternatives with a relatively greater conversion efficiency becomes less important as increases in socio-economic potential compensate for a loss in financial-economic viability. However, similar to the first two biomass procurement areas, at least eight of the top-ten-ranked alternatives in BPAs III and IV encompass bioenergy conversion system II, the aggregated, weighted score profiles of which represent a more valid reflection of the set of weights given by the expert group.

The application of MCDA proved to be an appealing and practical tool that organises and synthesises relevant information in a way that should lead decision makers to feel comfortable and confident about making a decision, as it minimises potential post-decision regret by ensuring satisfaction that all the criteria or factors have been properly taken into account. As was illustrated in the context of implementing bioenergy systems, MCDA is well suited to being integrated with performance-data-generating methods such as LCA and complementary financial- and socio-economic assessment methods. However, MCDA does not provide the 'single right answer', even within the context of the model used, as the concept of an optimum does not exist in a multi-criteria framework. Rather, its purpose is to produce insight in order to help decision makers make better decisions; to learn and understand the problem faced; the stakeholder priorities, values and objectives; and through exploring these in the context of the problem, to guide them in identifying a preferred course of action, whilst promoting transparency.

8.3 Recommendations

Following the outcome of this study, a number of recommendations can be put forward. The production of biomass for bioenergy in a short-ration coppice system is relatively new to South Africa. The availability of data related to this topic is limited and requires additional research and further validation of the current database in order to support similar studies in the future. Further, some recommendations deal with improvement to and application of the methods discussed in this study.

- In the context of land availability for biomass production, the combined use of geographic information systems and the biodiversity intactness index (BII), as well as the water footprint index (WF) could advance this study from a methodological point of view. The current approach limits the respective impacts due to land-use change by excluding sensitive areas, but does not quantify the respective impacts. The BII, for instance, is intended to provide a single, integrated measure of biodiversity, measuring the change in abundance across a wide range of well-known elements of biodiversity, relative to their levels in a chosen reference case. The application of the WF provides information on the volume of fresh water used for the production of a product (commodity, good or service) at the place where it was actually produced.
- In contrast to commercial forestry plantations, which are aimed at timber production and are characterised by long rotation cycles in order to produce high quality and dimension timber, short-rotation coppice (SRC) biomass production has far fewer requirements in terms of wood quality, and more emphasis is placed on the maximisation of volumetric production per time and area units. Hence, trees grown for bioenergy are to be harvested when reaching their maximum mean annual increment. Given the lack of experience of producing biomass in SRC systems in South Africa, additional research in terms of suitable tree species, their productivity rates, rotation lengths and other silvicultural parameters could improve the data quality, by providing sound and proven information. The use of improved genetic material/tree hybrids may, for instance, improve the growth rate, ease of cultivation, adaptability to site conditions, drought and frost resistance, or reduce the risk of invasion.
- In this context, another important consideration, for which additional research would present a useful and profound contribution, deals with the bulk densities of various types of comminuted and uncomminuted biomass at various moisture content levels from tree species grown for

bioenergy. The assumptions on the bulk density of the bioenergy feedstock made in this study are based on the input from a group of forestry experts, but further research is recommended to validate the applied values. Sound assumptions on feedstock bulk densities are of crucial importance, as they affect a variety of bioenergy system components, such as handling, transport and storage.

- Another aspect pertaining to bioenergy feedstock, for which additional research would improve the data quality for assessing lignocellulosic bioenergy systems, is an approximation of the ratios of the basic components of the trees used for bioenergy production (e.g. bark, stem, branches, etc.), which in turn is affected by silvicultural aspects such as number of trees per hectare, and rotation length, amongst others.
- The chemical composition of the bioenergy feedstock represents another crucial aspect, particularly in terms of potential bioenergy conversion efficiencies and related emissions. A simplified approach to determining the magnitude of the emissions was used in this study, applying the so-called thermo-chemical equilibrium and theoretical or stoichiometric oxygen/air requirement, which assumes the complete combustion of the feedstock. This, however, represents the lower limit of emissions, giving some indication of the emissions to expect. By using software packages such as the NASA chemical equilibrium programme or ASPEN, more accurate emission estimates for the assessed bioenergy conversion systems could be provided, but this would have gone beyond the scope of this study.
- A previous study by the author has already dealt with the financial-economic viability of biomass production for bioenergy, from a farmer's perspective. This was done by calculating the farm-gate price for biomass backwards, starting with the tariff paid by ESKOM, less the costs of bioenergy conversion, biomass upgrading, secondary transport, etc. (Von Doderer, 2009). Using the data and results from the present study to reassess the financial-economic impact on the various farm types found within the Cape Winelands District Municipality (CWDM) would provide additional information for a better understanding of this production system and for the implementation of such bioenergy systems.
- This leads to another very important aspect of implementing the bioenergy systems, from a managerial point of view. Once the policymakers of the CWDM have decided on a location and have selected the appropriate lignocellulosic bioenergy system, additional support will be required in terms of the organisation and planning phases of the implementation thereof. This includes, for instance, agreement on contractual terms between biomass producers and bioenergy producers, in order to minimise financial-economic risks on both sides. The biomass

producers need to ensure sufficient bioenergy feedstock supply before the bioenergy conversion plant commences generating electricity.

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ANNEXURES

Annexure 1: LCA results –LBS 1

Paarl	∑	Primary production	Forwarding	Harvesting	Comminution	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.43	0.61	0.14	0.22	0.19	0.00	0.27
ADP fossil [MJ]	24340734.13	6777362.08	2880466.74	5580608.67	3718611.61	0.00	5383685.03
AP [kg SO_2-Equiv.]	125768.85	4155.63	1094.60	538.06	2133.49	115925.50	1921.57
EP [kg Phosphate-Equiv.]	31936.04	1209.89	224.59	29.69	477.40	29607.69	386.77
FAETP inf. [kg DCB-Equiv.]	4153.76	915.83	479.74	1274.57	613.39	0.00	870.23
GWP 100 years [kg CO_2-Equiv.]	132794.05	-64309905.96	237653.74	154050.97	3476107.01	60120377.15	454511.16
HTP inf. [kg DCB-Equiv.]	611767.89	14149.37	8045.57	11556.80	12107.78	546596.71	19311.66
MAETP inf. [kg DCB-Equiv.]	80234139.97	21497245.58	9730829.71	18114892.40	12607743.19	0.00	18283429.09
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	9133.88	185.82	177.05	1733.50	267.09	6562.34	208.07
TETP inf. [kg DCB-Equiv.]	1369.29	334.51	157.48	391.76	199.92	0.00	285.61
Worcester							
(ADP elements) [kg Sb-Equiv.]	1.40	0.67	0.14	0.26	0.19	0.00	0.14
(ADP fossil) [MJ]	23740877.22	7760650.32	2880466.74	6577145.93	3718611.61	0.00	2804002.62
AP [kg SO_2-Equiv.]	125637.76	4849.22	1094.60	634.14	2133.49	115925.50	1000.82
EP [kg Phosphate-Equiv.]	31963.41	1417.29	224.59	35.00	477.40	29607.69	201.44
FAETP inf. [kg DCB-Equiv.]	4090.16	1041.61	479.74	1502.17	613.39	0.00	453.25
GWP 100 years [kg CO_2-Equiv.]	470765.64	-63781656.88	237653.74	181560.07	3476107.01	60120377.15	236724.56
HTP inf. [kg DCB-Equiv.]	606598.23	16169.50	8045.57	13620.51	12107.78	546596.71	10058.16
MAETP inf. [kg DCB-Equiv.]	77822517.12	24611630.30	9730829.71	21349694.61	12607743.19	0.00	9522619.32
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	9366.50	208.59	177.05	2043.05	267.09	6562.34	108.37
TETP inf. [kg DCB-Equiv.]	1349.95	382.07	157.48	461.72	199.92	0.00	148.76
Ashton							
(ADP elements) [kg Sb-Equiv.]	1.61	0.89	0.14	0.30	0.19	0.00	0.10
(ADP fossil) [MJ]	25506797.63	9467175.79	2880466.74	7533821.70	3718611.61	0.00	1906721.78
AP [kg SO_2-Equiv.]	126238.52	5678.00	1094.60	726.38	2133.49	115925.50	680.56
EP [kg Phosphate-Equiv.]	32132.22	1645.46	224.59	40.09	477.40	29607.69	136.98
FAETP inf. [kg DCB-Equiv.]	4411.23	1289.22	479.74	1720.66	613.39	0.00	308.21
GWP 100 years [kg CO_2-Equiv.]	1358009.50	-62845069.90	237653.74	207968.80	3476107.01	60120377.15	160972.70
HTP inf. [kg DCB-Equiv.]	609002.08	19810.80	8045.57	15601.68	12107.78	546596.71	6839.55
MAETP inf. [kg DCB-Equiv.]	83304513.10	30035454.34	9730829.71	24455104.73	12607743.19	0.00	6475381.14
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	9685.83	265.43	177.05	2340.22	267.09	6562.34	73.69
TETP inf. [kg DCB-Equiv.]	1456.07	468.64	157.48	528.88	199.92	0.00	101.15
Rural Cederberge							
(ADP elements) [kg Sb-Equiv.]	1.66	0.98	0.14	0.25	0.19	0.00	0.00
(ADP fossil) [MJ]	23950494	9054349	2880467	6278185	3718612	0	0
AP [kg SO_2-Equiv.]	125460	4981	1095	605	2133	115926	0
EP [kg Phosphate-Equiv.]	31904	1416	225	33	477	29608	0
FAETP inf. [kg DCB-Equiv.]	4122	1268	480	1434	613	0	0
GWP 100 years [kg CO_2-Equiv.]	1346380	-62831507	237654	173307	3476107	60120377	0
HTP inf. [kg DCB-Equiv.]	606103	19109	8046	13001	12108	546597	0
MAETP inf. [kg DCB-Equiv.]	78322292	28748179	9730830	20379254	12607743	0	0
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	9309	275	177	1950	267	6562	0
TETP inf. [kg DCB-Equiv.]	1358	453	157	441	200	0	0

Annexure 2: LCA results –LBS 2

Paarl	∑	Primary production	Forwarding	Harvesting	Comminution	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.21	0.52	0.12	0.19	0.16	0.00	0.21
ADP fossil [MJ]	20567400	5834261	2479637	4804042	3201150	0	4248311
AP [kg SO_2-Equiv.]	83622	3577	942	463	1837	75287	1516
EP [kg Phosphate-Equiv.]	21092	1042	193	26	411	19116	305
FAETP inf. [kg DCB-Equiv.]	3513	788	413	1097	528	0	687
GWP 100 years [kg CO_2-Equiv.]	81710	-55360890	204583	132614	2992391	51754353	358659
HTP inf. [kg DCB-Equiv.]	231311	12180	6926	9949	10423	176594	15239
MAETP inf. [kg DCB-Equiv.]	67757594	18505806	8376741	1559413	10853318	0	14427606
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	6476	160	152	1492	230	4277	164
TETP inf. [kg DCB-Equiv.]	1158	288	136	337	172	0	225
Worcester							
ADP elements [kg Sb-Equiv.]	1.20	0.58	0.12	0.23	0.16	0.00	0.12
ADP fossil [MJ]	20340674	6680721	2479637	5661906	3201150	0	2317260
AP [kg SO_2-Equiv.]	83613	4174	942	546	1837	75287	827
EP [kg Phosphate-Equiv.]	21137	1220	193	30	411	19116	166
FAETP inf. [kg DCB-Equiv.]	3505	897	413	1293	528	0	375
GWP 100 years [kg CO_2-Equiv.]	397105	-54906149	204583	156295	2992391	51754353	195632
HTP inf. [kg DCB-Equiv.]	227900	13919	6926	11725	10423	176594	8312
MAETP inf. [kg DCB-Equiv.]	66665260	21186810	8376741	18378788	10853318	0	7869603
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	6687	180	152	1759	230	4277	90
TETP inf. [kg DCB-Equiv.]	1157	329	136	397	172	0	123
Ashton							
ADP elements [kg Sb-Equiv.]	1.38	0.76	0.12	0.26	0.16	0.00	0.08
ADP fossil [MJ]	21860858	8149775	2479637	6485456	3201150	0	1544840
AP [kg SO_2-Equiv.]	84130	4888	942	625	1837	75287	551
EP [kg Phosphate-Equiv.]	21282	1416	193	35	411	19116	111
FAETP inf. [kg DCB-Equiv.]	3782	1110	413	1481	528	0	250
GWP 100 years [kg CO_2-Equiv.]	1160885	-54099893	204583	179029	2992391	51754353	130421
HTP inf. [kg DCB-Equiv.]	229969	17054	6926	13431	10423	176594	5541
MAETP inf. [kg DCB-Equiv.]	71384411	25855884	8376741	21052066	10853318	0	5246402
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	6962	228	152	2015	230	4277	60
TETP inf. [kg DCB-Equiv.]	1248	403	136	455	172	0	82
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.43	0.84	0.12	0.22	0.16	0.00	0.09
ADP fossil [MJ]	20714226	7794395	2479637	5404547	3201150	0	1834498
AP [kg SO_2-Equiv.]	83529	4288	942	521	1837	75287	655
EP [kg Phosphate-Equiv.]	21099	1219	193	29	411	19116	132
FAETP inf. [kg DCB-Equiv.]	3564	1092	413	1234	528	0	297
GWP 100 years [kg CO_2-Equiv.]	1167176	-54088217	204583	149191	2992391	51754353	154875
HTP inf. [kg DCB-Equiv.]	228166	16450	6926	11192	10423	176594	6580
MAETP inf. [kg DCB-Equiv.]	67751289	24747739	8376741	17543388	10853318	0	6230103
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	6645	236	152	1679	230	4277	71
TETP inf. [kg DCB-Equiv.]	1174	390	136	379	172	0	97

Annexure 3: LCA results –LBS 3

Paarl	∑	Primary production	Forwarding	Harvesting	Comminution	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	2.02	0.86	0.20	0.32	0.26	0.00	0.38
ADP fossil [MJ]	34385764	9618592	4088026	7920132	5277541	0	7481473
AP [kg SO_2-Equiv.]	216723	5898	1553	764	3028	202810	2670
EP [kg Phosphate-Equiv.]	55235	1717	319	42	678	51942	537
FAETP inf. [kg DCB-Equiv.]	5869	1300	681	1809	871	0	1209
GWP 100 years [kg CO_2-Equiv.]	97458	-91270137	337284	218633	4933373	85246691	631614
HTP inf. [kg DCB-Equiv.]	571633	20081	11418	16402	17184	479712	26837
MAETP inf. [kg DCB-Equiv.]	113329597	30509399	13810223	25709083	17893207	0	25407685
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	16418	264	251	2460	379	12775	289
TETP inf. [kg DCB-Equiv.]	1935	475	223	556	284	0	397
Worcester							
ADP elements [kg Sb-Equiv.]	1.99	0.95	0.20	0.37	0.26	0.00	0.20
ADP fossil [MJ]	33693614	11014098	4088026	9334441	5277541	0	3979507
AP [kg SO_2-Equiv.]	216594	6882	1553	900	3028	202810	1420
EP [kg Phosphate-Equiv.]	55286	2011	319	50	678	51942	286
FAETP inf. [kg DCB-Equiv.]	5805	1478	681	2132	871	0	643
GWP 100 years [kg CO_2-Equiv.]	590554	-90520434	337284	257674	4933373	85246691	335965
HTP inf. [kg DCB-Equiv.]	564867	22948	11418	19331	17184	479712	14275
MAETP inf. [kg DCB-Equiv.]	110447554	34929407	13810223	30299991	17893207	0	13514726
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	16755	296	251	2900	379	12775	154
TETP inf. [kg DCB-Equiv.]	1916	542	223	655	284	0	211
Ashton							
ADP elements [kg Sb-Equiv.]	2.29	1.26	0.20	0.43	0.26	0.00	0.14
ADP fossil [MJ]	36199849	13436039	4088026	10692178	5277541	0	2706065
AP [kg SO_2-Equiv.]	217446	8058	1553	1031	3028	202810	966
EP [kg Phosphate-Equiv.]	55525	2335	319	57	678	51942	194
FAETP inf. [kg DCB-Equiv.]	6261	1830	681	2442	871	0	437
GWP 100 years [kg CO_2-Equiv.]	1849752	-89191207	337284	295154	4933373	85246691	228456
HTP inf. [kg DCB-Equiv.]	568279	28116	11418	22142	17184	479712	9707
MAETP inf. [kg DCB-Equiv.]	118227732	42627026	13810223	34707262	17893207	0	9190014
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	17208	377	251	3321	379	12775	105
TETP inf. [kg DCB-Equiv.]	2066	665	223	751	284	0	144
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.36	1.39	0.20	0.36	0.26	0.00	0.15
ADP fossil [MJ]	34150287	12850146	4088026	8910148	5277541	0	3024425
AP [kg SO_2-Equiv.]	216398	7069	1553	859	3028	202810	1079
EP [kg Phosphate-Equiv.]	55213	2009	319	47	678	51942	217
FAETP inf. [kg DCB-Equiv.]	5875	1800	681	2035	871	0	489
GWP 100 years [kg CO_2-Equiv.]	1846685	-89171958	337284	245962	4933373	85246691	255333
HTP inf. [kg DCB-Equiv.]	564735	27120	11418	18452	17184	479712	10849
MAETP inf. [kg DCB-Equiv.]	111697435	40800094	13810223	28922718	17893207	0	10271192
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	16680	390	251	2768	379	12775	117
TETP inf. [kg DCB-Equiv.]	1936	643	223	625	284	0	160

Annexure 4: LCA results –LBS 4

Paarl	∑	Prim. production	Forwarding	Harvesting	Comminution	Conversion	Upgrading	Transp.	Transp.
ADP elements [kg Sb-Equiv.]	1.52	0.74	0.17	0.27	0.23	0.00	0.00	0.028817438	0.082857162
ADP fossil [MJ]	25277401	8245734	3504544	6789694	4524280	0	0	571099	1642049
AP [kg SO_2-Equiv.]	183359	5056	1332	655	2596	148246	24680	204	591
EP [kg Phosphate-Equiv.]	46819	1472	273	36	581	38171	6125	41	119
FAETP inf. [kg DCB-Equiv.]	4353	1114	584	1551	746	0	0	92	265
GWP 100 years [kg CO_2-Equiv.]	-270989	-78243187	289143	187427	4229235	69969071	3110473	48214	138633
HTP inf. [kg DCB-Equiv.]	472879	17215	9789	14061	14731	352463	56629	2049	5943
MAETP inf. [kg DCB-Equiv.]	82888884	26154804	11839096	22039636	15339317	0	0	1939499	5576532
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.000194505	0.00055925
POCP [kg Ethene-Equiv.]	13862	226	215	2109	325	9482	1418	22	64
TETP inf. [kg DCB-Equiv.]	1436	407	192	477	243	0	0	30	87
Worcester								**of bio-char**	**of bio-oil**
ADP elements [kg Sb-Equiv.]	1.59	0.82	0.17	0.32	0.23	0.00	0.00	0.015328425	0.044072959
ADP fossil [MJ]	26650231	9442060	3504544	8002140	4524280	0	0	303776	873431
AP [kg SO_2-Equiv.]	183947	5900	1332	772	2596	148246	24680	108	314
EP [kg Phosphate-Equiv.]	47002	1724	273	43	581	38171	6125	22	63
FAETP inf. [kg DCB-Equiv.]	4615	1267	584	1828	746	0	0	49	141
GWP 100 years [kg CO_2-Equiv.]	317718	-77600488	289143	220897	4229235	69969071	3110473	25646	73741
HTP inf. [kg DCB-Equiv.]	474107	19673	9789	16572	14731	352463	56629	1090	3161
MAETP inf. [kg DCB-Equiv.]	87095533	29943946	11839096	25975285	15339317	0	0	1031648	2966241
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00010346	0.000297473
POCP [kg Ethene-Equiv.]	14226	254	215	2486	325	9482	1418	12	34
TETP inf. [kg DCB-Equiv.]	1524	465	192	562	243	0	0	16	46
Ashton									
ADP elements [kg Sb-Equiv.]	1.88	1.08	0.17	0.37	0.23	0.00	0.00	0.010423329	0.029969612
ADP fossil [MJ]	29513731	11518319	3504544	9166087	4524280	0	0	206568	593933
AP [kg SO_2-Equiv.]	184933	6908	1332	884	2596	148246	24680	74	214
EP [kg Phosphate-Equiv.]	47259	2002	273	49	581	38171	6125	15	43
FAETP inf. [kg DCB-Equiv.]	5121	1569	584	2093	746	0	0	33	96
GWP 100 years [kg CO_2-Equiv.]	1457551	-76460982	289143	253027	4229235	69969071	3110473	17439	50144
HTP inf. [kg DCB-Equiv.]	479587	24103	9789	18982	14731	352463	56629	741	2149
MAETP inf. [kg DCB-Equiv.]	96193373	36542888	11839096	29753508	15339317	0	0	701521	2017044
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00	7.03529E-05	0.000202282
POCP [kg Ethene-Equiv.]	14642	323	215	2847	325	9482	1418	8	23
TETP inf. [kg DCB-Equiv.]	1691	570	192	643	243	0	0	11	32
Rural Cederberge									
ADP elements [kg Sb-Equiv.]	1.94	1.19	0.17	0.31	0.23	0.00	0.00	0.011649603	0.033495448
ADP fossil [MJ]	27577957	11016049	3504544	7638406	4524280	0	0	230870	663807
AP [kg SO_2-Equiv.]	183971	6060	1332	736	2596	148246	24680	82	239
EP [kg Phosphate-Equiv.]	46978	1722	273	41	581	38171	6125	17	48
FAETP inf. [kg DCB-Equiv.]	4762	1543	584	1745	746	0	0	37	107
GWP 100 years [kg CO_2-Equiv.]	1439832	-76444480	289143	210856	4229235	69969071	3110473	19491	56043
HTP inf. [kg DCB-Equiv.]	475910	23249	9789	15818	14731	352463	56629	828	2402
MAETP inf. [kg DCB-Equiv.]	89988111	34976713	11839096	24794590	15339317	0	0	784053	2254343
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	7.86297E-05	0.00022608
POCP [kg Ethene-Equiv.]	14182	334	215	2373	325	9482	1418	9	26
TETP inf. [kg DCB-Equiv.]	1570	551	192	536	243	0	0	12	35

Annexure 5: **LCA results –LBS 5**

Paarl	**∑**	**Prim. production**	**Forwarding**	**Harvesting**	**Comminution**	**bio-char for sale**	**Conversion**	**Upgrading**	**transport**	**transport**
ADP elements [kg Sb-Equiv.]	2.02	0.98	0.23	0.36	0.30	0.00	0.00	0.00	0.041281032	0.118693034
ADP fossil [MJ]	33618583	10885596	4626519	8963406	5972722	0	0	0	818101	2352239
AP [kg SO_2-Equiv.]	116761	6675	1758	864	3427	0	70317	32582	292	846
EP [kg Phosphate-Equiv.]	29481	1943	361	48	767	0	18047	8086	59	171
FAETP inf. [kg DCB-Equiv.]	5786	1471	771	2047	985	0	0	0	132	380
GWP 100 years [kg CO_2-Equiv.]	-36009946	-103292643	381712	247432	5583219	8929400	47766987	4106287	69067	198593
HTP inf. [kg DCB-Equiv.]	326526	22726	12923	18562	19447	0	166661	74759	2935	8513
MAETP inf. [kg DCB-Equiv.]	110270103	34528231	15629367	29095597	20250179	0	0	0	2778336	7988393
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.000278629	0.000801126
POCP [kg Ethene-Equiv.]	10536	298	284	2784	429	0	4745	1871	32	92
TETP inf. [kg DCB-Equiv.]	1909	537	253	629	321	0	0	0	43	125
Worcester									**of bio-char**	**of bio-oil**
ADP elements [kg Sb-Equiv.]	2.11	1.08	0.23	0.42	0.30	0.00	0.00	0.00	0.021854664	0.062837489
ADP fossil [MJ]	35306595	12464924	4626519	10564015	5972722	0	0	0	433112	1245303
AP [kg SO_2-Equiv.]	117494	7789	1758	1019	3427	0	70317	32582	155	448
EP [kg Phosphate-Equiv.]	29715	2276	361	56	767	0	18047	8086	31	90
FAETP inf. [kg DCB-Equiv.]	6113	1673	771	2413	985	0	0	0	70	201
GWP 100 years [kg CO_2-Equiv.]	-35243262	-102444185	381712	291616	5583219	8929400	47766987	4106287	36565	105137
HTP inf. [kg DCB-Equiv.]	327698	25971	12923	21877	19447	0	166661	74759	1554	4507
MAETP inf. [kg DCB-Equiv.]	115401281	39530463	15629367	34291239	20250179	0	0	0	1470884	4229149
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.000147509	0.000424126
POCP [kg Ethene-Equiv.]	11012	335	284	3281	429	0	4745	1871	17	49
TETP inf. [kg DCB-Equiv.]	2018	614	253	742	321	0	0	0	23	66
Ashton										
ADP elements [kg Sb-Equiv.]	2.51	1.42	0.23	0.49	0.30	0.00	0.00	0.00	0.02	0.06
ADP fossil [MJ]	39459822	15205894	4626519	12100599	5972722	0	0	0	401030	1153058
AP [kg SO_2-Equiv.]	118928	9120	1758	1167	3427	0	70317	32582	143	415
EP [kg Phosphate-Equiv.]	30080	2643	361	64	767	0	18047	8086	29	84
FAETP inf. [kg DCB-Equiv.]	6841	2071	771	2764	985	0	0	0	65	186
GWP 100 years [kg CO_2-Equiv.]	-33707023	-100939867	381712	334033	5583219	8929400	47766987	4106287	33856	97349
HTP inf. [kg DCB-Equiv.]	336280	31820	12923	25059	19447	0	166661	74759	1439	4173
MAETP inf. [kg DCB-Equiv.]	128678457	48242046	15629367	39279056	20250179	0	0	0	1361929	3915879
ODP, steady state [kg R11-Equiv.]	0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	11575	426	284	3759	429	0	4745	1871	15	45
TETP inf. [kg DCB-Equiv.]	2259	753	253	849	321	0	0	0	21	61
Rural Cederberge										
ADP elements [kg Sb-Equiv.]	2.56	1.57	0.23	0.40	0.30	0.00	0.00	0.00	0.02	0.04
ADP fossil [MJ]	36407004	14542824	4626519	10083832	5972722	0	0	0	304783	876324
AP [kg SO_2-Equiv.]	117480	8000	1758	972	3427	0	70317	32582	109	315
EP [kg Phosphate-Equiv.]	29674	2274	361	54	767	0	18047	8086	22	64
FAETP inf. [kg DCB-Equiv.]	6287	2037	771	2303	985	0	0	0	49	142
GWP 100 years [kg CO_2-Equiv.]	-33772400	-100918083	381712	278361	5583219	8929400	47766987	4106287	25731	73986
HTP inf. [kg DCB-Equiv.]	329630	30693	12923	20882	19447	0	166661	74759	1093	3171
MAETP inf. [kg DCB-Equiv.]	118797690	46174463	15629367	32732547	20250179	0	0	0	1035066	2976068
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	10949	441	284	3132	429	0	4745	1871	12	34
TETP inf. [kg DCB-Equiv.]	2072	728	253	708	321	0	0	0	16	46

Annexure 6: LCA results –LBS 6

Paarl	∑	Primary production	Forwarding	Harvesting	Conversion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.23	0.59	0.14	0.22	0.00	0.01	0.28
ADP fossil [MJ]	31676650	6569892	2792289	5409774	0	11411139	5493556
AP [kg SO_2-Equiv.]	137612	4028	1061	522	115926	14115	1961
EP [kg Phosphate-Equiv.]	32047	1173	218	29	29608	625	395
FAETP inf. [kg DCB-Equiv.]	5107	888	465	1236	0	1631	888
GWP 100 years [kg CO_2-Equiv.]	-182953	-62341235	230379	149335	60120377	1194405	463787
HTP inf. [kg DCB-Equiv.]	938287	13716	7799	11203	546597	339266	19706
MAETP inf. [kg DCB-Equiv.]	3390850873	20839167	9432947	17560355	0	3324361844	18656560
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	9533	180	172	1680	6562	726	212
TETP inf. [kg DCB-Equiv.]	5025	324	153	380	0	3877	291
Worcester							
ADP elements [kg Sb-Equiv.]	1.19	0.65	0.14	0.26	0.00	0.01	0.14
ADP fossil [MJ]	30963540	7523079	2792289	6375805	0	11411139	2861227
AP [kg SO_2-Equiv.]	137438	4701	1061	615	115926	14115	1021
EP [kg Phosphate-Equiv.]	32064	1374	218	34	29608	625	206
FAETP inf. [kg DCB-Equiv.]	5024	1010	465	1456	0	1631	462
GWP 100 years [kg CO_2-Equiv.]	133561	-61829157	230379	176002	60120377	1194405	241556
HTP inf. [kg DCB-Equiv.]	932804	15675	7799	13204	546597	339266	10263
MAETP inf. [kg DCB-Equiv.]	3388066095	23858213	9432947	20696133	0	3324361844	9716958
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	9754	202	172	1981	6562	726	111
TETP inf. [kg DCB-Equiv.]	5000	370	153	448	0	3877	152
Ashton							
ADP elements [kg Sb-Equiv.]	1.39	0.86	0.14	0.29	0.00	0.01	0.10
ADP fossil [MJ]	32629622	9177364	2792289	7303195	0	11411139	1945634
AP [kg SO_2-Equiv.]	138004	5504	1061	704	115926	14115	694
EP [kg Phosphate-Equiv.]	32224	1595	218	39	29608	625	140
FAETP inf. [kg DCB-Equiv.]	5328	1250	465	1668	0	1631	314
GWP 100 years [kg CO_2-Equiv.]	989780	-60921241	230379	201602	60120377	1194405	164258
HTP inf. [kg DCB-Equiv.]	934970	19204	7799	15124	546597	339266	6979
MAETP inf. [kg DCB-Equiv.]	3393224803	29116002	9432947	23706479	0	3324361844	6607532
ODP, steady state [kg R11-Equiv.]	0.05	0.03	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	10062	257	172	2269	6562	726	75
TETP inf. [kg DCB-Equiv.]	5100	454	153	513	0	3877	103
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.44	0.95	0.14	0.24	0.00	0.01	0.10
ADP fossil [MJ]	31126682	8777175	2792289	6085995	0	11411139	2060084
AP [kg SO_2-Equiv.]	137252	4828	1061	587	115926	14115	735
EP [kg Phosphate-Equiv.]	32003	1372	218	32	29608	625	148
FAETP inf. [kg DCB-Equiv.]	5048	1229	465	1390	0	1631	333
GWP 100 years [kg CO_2-Equiv.]	978989	-60908093	230379	168002	60120377	1194405	173920
HTP inf. [kg DCB-Equiv.]	932179	18524	7799	12603	546597	339266	7390
MAETP inf. [kg DCB-Equiv.]	3388414533	27868133	9432947	19755399	0	3324361844	6996210
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	9697	266	172	1890	6562	726	80
TETP inf. [kg DCB-Equiv.]	5006	439	153	427	0	3877	109

Annexure 7: LCA results – LBS 7

Paarl	∑	Primary production	Forwarding	Harvesting,	Conversion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.04	0.51	0.12	0.19	0.00	0.01	0.22
ADP fossil [MJ]	26874608	5655662	2403729	4656979	0	9823227	4335011
AP [kg SO_2-Equiv.]	93815	3468	913	449	75287	12151	1547
EP [kg Phosphate-Equiv.]	21187	1010	187	25	19116	538	311
FAETP inf. [kg DCB-Equiv.]	4333	764	400	1064	0	1404	701
GWP 100 years [kg CO_2-Equiv.]	-190765	-53666169	198320	128554	51754353	1028198	365978
HTP inf. [kg DCB-Equiv.]	512365	11808	6714	9644	176594	292056	15550
MAETP inf. [kg DCB-Equiv.]	2917660197	17939302	8120310	15116752	0	2861761786	14722047
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	6819	155	148	1447	4277	625	168
TETP inf. [kg DCB-Equiv.]	4305	279	131	327	0	3338	230
Worcester							
ADP elements [kg Sb-Equiv.]	1.02	0.56	0.12	0.22	0.00	0.01	0.12
ADP fossil [MJ]	26556299	6476209	2403729	5488583	0	9823227	2364551
AP [kg SO_2-Equiv.]	93770	4047	913	529	75287	12151	844
EP [kg Phosphate-Equiv.]	21223	1183	187	29	19116	538	170
FAETP inf. [kg DCB-Equiv.]	4309	869	400	1254	0	1404	382
GWP 100 years [kg CO_2-Equiv.]	106658	-53225349	198320	151511	51754353	1028198	199624
HTP inf. [kg DCB-Equiv.]	508705	13493	6714	11366	176594	292056	8482
MAETP inf. [kg DCB-Equiv.]	2916266709	20538234	8120310	17816172	0	2861761786	8030208
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	7020	174	148	1705	4277	625	91
TETP inf. [kg DCB-Equiv.]	4299	319	131	385	0	3338	125
Ashton							
ADP elements [kg Sb-Equiv.]	1.20	0.74	0.12	0.25	0.00	0.01	0.08
ADP fossil [MJ]	27990538	7900292	2403729	6286922	0	9823227	1576368
AP [kg SO_2-Equiv.]	94258	4738	913	606	75287	12151	563
EP [kg Phosphate-Equiv.]	21361	1373	187	33	19116	538	113
FAETP inf. [kg DCB-Equiv.]	4571	1076	400	1436	0	1404	255
GWP 100 years [kg CO_2-Equiv.]	843730	-52443774	198320	173549	51754353	1028198	133083
HTP inf. [kg DCB-Equiv.]	510570	16532	6714	13019	176594	292056	5655
MAETP inf. [kg DCB-Equiv.]	2920707560	25064378	8120310	20407615	0	2861761786	5353472
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	7285	222	148	1953	4277	625	61
TETP inf. [kg DCB-Equiv.]	4385	391	131	441	0	3338	84
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.24	0.81	0.12	0.21	0.00	0.01	0.09
ADP fossil [MJ]	26893786	7555791	2403729	5239102	0	9823227	1871937
AP [kg SO_2-Equiv.]	93680	4156	913	505	75287	12151	668
EP [kg Phosphate-Equiv.]	21185	1181	187	28	19116	538	134
FAETP inf. [kg DCB-Equiv.]	4362	1058	400	1197	0	1404	303
GWP 100 years [kg CO_2-Equiv.]	851076	-52432455	198320	144624	51754353	1028198	158036
HTP inf. [kg DCB-Equiv.]	508875	15947	6714	10850	176594	292056	6715
MAETP inf. [kg DCB-Equiv.]	2917235845	23990155	8120310	17006346	0	2861761786	6357248
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	6979	229	148	1627	4277	625	72
TETP inf. [kg DCB-Equiv.]	4314	378	131	368	0	3338	99

Annexure 8: LCA results – LBS 8

Paarl	∑	Primary production	Forwarding	Harvesting	Upgrading	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.73	0.84	0.19	0.31	0.00	0.01	0.39
ADP fossil [MJ]	44793821	9324146	3962883	7677679	0	16194958	7634156
AP [kg SO2-Equiv.]	233530	5717	1506	740	202810	20032	2725
EP [kg Phosphate-Equiv.]	55392	1665	309	41	51942	887	548
FAETP inf. [kg DCB-Equiv.]	7222	1260	660	1754	0	2315	1234
GWP 100 years [kg CO2-Equiv.]	-350931	-88476153	326959	211940	85246691	1695127	644504
HTP inf. [kg DCB-Equiv.]	1035025	19466	11069	15900	479712	481494	27384
MAETP inf. [kg DCB-Equiv.]	4811824007	29575437	13387461	24922070	0	4718012829	25926209
ODP, steady state [kg R11-Equiv.]	0.07	0.03	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	16985	256	244	2385	12775	1031	295
TETP inf. [kg DCB-Equiv.]	7124	460	217	539	0	5503	405
Worcester							
ADP elements [kg Sb-Equiv.]	1.69	0.92	0.19	0.36	0.00	0.01	0.20
ADP fossil [MJ]	43944187	10676932	3962883	9048693	0	16194958	4060721
AP [kg SO2-Equiv.]	233341	6671	1506	872	202810	20032	1449
EP [kg Phosphate-Equiv.]	55428	1950	309	48	51942	887	292
FAETP inf. [kg DCB-Equiv.]	7131	1433	660	2067	0	2315	656
GWP 100 years [kg CO2-Equiv.]	111986	-87749400	326959	249786	85246691	1695127	342822
HTP inf. [kg DCB-Equiv.]	1027825	22246	11069	18739	479712	481494	14566
MAETP inf. [kg DCB-Equiv.]	4808423406	33860139	13387461	29372440	0	4718012829	13790537
ODP, steady state [kg R11-Equiv.]	0.07	0.03	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	17304	287	244	2811	12775	1031	157
TETP inf. [kg DCB-Equiv.]	7096	526	217	635	0	5503	215
Ashton							
ADP elements [kg Sb-Equiv.]	1.98	1.22	0.19	0.42	0.00	0.01	0.14
ADP fossil [MJ]	46308729	13024732	3962883	10364866	0	16194958	2761290
AP [kg SO2-Equiv.]	234144	7812	1506	999	202810	20032	986
EP [kg Phosphate-Equiv.]	55656	2264	309	55	51942	887	198
FAETP inf. [kg DCB-Equiv.]	7562	1774	660	2367	0	2315	446
GWP 100 years [kg CO2-Equiv.]	1327151	-86460864	326959	286119	85246691	1695127	233119
HTP inf. [kg DCB-Equiv.]	1030899	27255	11069	21464	479712	481494	9905
MAETP inf. [kg DCB-Equiv.]	4815744767	41322117	13387461	33644795	0	4718012829	9377565
ODP, steady state [kg R11-Equiv.]	0.08	0.04	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	17741	365	244	3220	12775	1031	107
TETP inf. [kg DCB-Equiv.]	7238	645	217	728	0	5503	146
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.05	1.34	0.19	0.35	0.00	0.01	0.16
ADP fossil [MJ]	44338151	12456774	3962883	8637388	0	16194958	3086148
AP [kg SO2-Equiv.]	233134	6852	1506	833	202810	20032	1102
EP [kg Phosphate-Equiv.]	55354	1948	309	46	51942	887	222
FAETP inf. [kg DCB-Equiv.]	7191	1745	660	1973	0	2315	499
GWP 100 years [kg CO2-Equiv.]	1325550	-86442205	326959	238432	85246691	1695127	260544
HTP inf. [kg DCB-Equiv.]	1027522	26290	11069	17887	479712	481494	11070
MAETP inf. [kg DCB-Equiv.]	4809469539	39551112	13387461	28037329	0	4718012829	10480808
ODP, steady state [kg R11-Equiv.]	0.07242	0.03124	0.00138	0.00293	0.00000	0.03582	0.00105
POCP [kg Ethene-Equiv.]	17230	378	244	2683	12775	1031	119
TETP inf. [kg DCB-Equiv.]	7113	623	217	606	0	5503	164

Annexure 9: LCA results – LBS 9

Paarl	∑	Primary production	Harvesting	Comminution	Forwarding	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	2.15	0.87	0.66	0.14	0.19	0.00	0.29
ADP fossil [MJ]	38511285	9681946	16442865	2788959	3877350	0	5720165
AP [kg SO2-Equiv.]	129314	5937	1585	1600	2225	115926	2042
EP [kg Phosphate-Equiv.]	32690	1728	87	358	498	29608	411
FAETP inf. [kg DCB-Equiv.]	7088	1308	3755	460	640	0	925
GWP 100 years [kg CO2-Equiv.]	33665	-91871294	27578587	3398217	324860	60120377	482918
HTP inf. [kg DCB-Equiv.]	643085	20213	34051	9081	12625	546597	20519
MAETP inf. [kg DCB-Equiv.]	126112474	30710351	53374237	9455807	13145936	0	19426143
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	12635	265	5108	200	278	6562	221
TETP inf. [kg DCB-Equiv.]	2294	478	1154	150	208	0	303
Worcester							
ADP elements [kg Sb-Equiv.]	2.22	0.96	0.78	0.14	0.19	0.00	0.15
ADP fossil [MJ]	40160365	11086643	19379091	2788959	3877350	0	3028323
AP [kg SO2-Equiv.]	129627	6927	1868	1600	2225	115926	1081
EP [kg Phosphate-Equiv.]	32809	2025	103	358	498	29608	218
FAETP inf. [kg DCB-Equiv.]	7503	1488	4426	460	640	0	490
GWP 100 years [kg CO2-Equiv.]	642105	-91116653	27659641	3398217	324860	60120377	255663
HTP inf. [kg DCB-Equiv.]	642396	23099	40132	9081	12625	546597	10863
MAETP inf. [kg DCB-Equiv.]	130950995	35159472	62905350	9455807	13145936	0	10284429
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	13476	298	6020	200	278	6562	117
TETP inf. [kg DCB-Equiv.]	2425	546	1360	150	208	0	161
Ashton							
ADP elements [kg Sb-Equiv.]	2.63	1.27	0.89	0.14	0.19	0.00	0.14
ADP fossil [MJ]	45192716	13524537	22197868	2788959	3877350	0	2804003
AP [kg SO2-Equiv.]	131003	8111	2140	1600	2225	115926	1001
EP [kg Phosphate-Equiv.]	33134	2351	118	358	498	29608	201
FAETP inf. [kg DCB-Equiv.]	8464	1842	5070	460	640	0	453
GWP 100 years [kg CO2-Equiv.]	2038960	-89778671	27737452	3398217	324860	60120377	236725
HTP inf. [kg DCB-Equiv.]	652631	28301	45969	9081	12625	546597	10058
MAETP inf. [kg DCB-Equiv.]	147087374	42907792	72055219	9455807	13145936	0	9522619
ODP, steady state [kg R11-Equiv.]	0.05	0.04	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14424	379	6895	200	278	6562	108
TETP inf. [kg DCB-Equiv.]	2735	669	1558	150	208	0	149
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.60	1.40	0.74	0.14	0.19	0.00	0.12
ADP fossil [MJ]	40566838	12934784	18498223	2788959	3877350	0	2467522
AP [kg SO2-Equiv.]	129530	7115	1784	1600	2225	115926	881
EP [kg Phosphate-Equiv.]	32762	2022	98	358	498	29608	177
FAETP inf. [kg DCB-Equiv.]	7535	1812	4225	460	640	0	399
GWP 100 years [kg CO2-Equiv.]	1927801	-89759296	27635325	3398217	324860	60120377	208318
HTP inf. [kg DCB-Equiv.]	642760	27299	38308	9081	12625	546597	8851
MAETP inf. [kg DCB-Equiv.]	132096492	41068827	60046016	9455807	13145936	0	8379905
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	13275	392	5746	200	278	6562	95
TETP inf. [kg DCB-Equiv.]	2435	647	1299	150	208	0	131

Annexure 10: LCA results – LBS 10

Paarl	∑	Primary production	Harvesting	Comminution	Forwarding	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.84	0.75	0.57	0.12	0.17	0.00	0.24
ADP fossil [MJ]	32959159	8334659	14154765	2400862	3337799	0	4731073
AP [kg SO2-Equiv.]	86743	5111	1365	1377	1915	75287	1689
EP [kg Phosphate-Equiv.]	21756	1488	75	308	429	19116	340
FAETP inf. [kg DCB-Equiv.]	6070	1126	3233	396	551	0	765
GWP 100 years [kg CO2-Equiv.]	12678	-79086986	23740902	2925340	279654	51754353	399415
HTP inf. [kg DCB-Equiv.]	258963	17401	29313	7817	10868	176594	16971
MAETP inf. [kg DCB-Equiv.]	107907550	26436866	45946969	8139989	11316619	0	16067107
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	9497	229	4397	172	240	4277	183
TETP inf. [kg DCB-Equiv.]	1965	411	994	129	179	0	251
Worcester							
ADP elements [kg Sb-Equiv.]	1.91	0.82	0.67	0.12	0.17	0.00	0.13
ADP fossil [MJ]	34475316	9543887	16682402	2400862	3337799	0	2510365
AP [kg SO2-Equiv.]	87047	5963	1608	1377	1915	75287	896
EP [kg Phosphate-Equiv.]	21865	1743	89	308	429	19116	180
FAETP inf. [kg DCB-Equiv.]	6443	1281	3810	396	551	0	406
GWP 100 years [kg CO2-Equiv.]	544602	-78437356	23810676	2925340	279654	51754353	211935
HTP inf. [kg DCB-Equiv.]	258716	19885	34547	7817	10868	176594	9005
MAETP inf. [kg DCB-Equiv.]	112400668	30266872	54151785	8139989	11316619	0	8525404
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	10225	257	5182	172	240	4277	97
TETP inf. [kg DCB-Equiv.]	2083	470	1171	129	179	0	133
Ashton							
ADP elements [kg Sb-Equiv.]	2.27	1.09	0.77	0.12	0.17	0.00	0.12
ADP fossil [MJ]	38903944	11642536	19108933	2400862	3337799	0	2413813
AP [kg SO2-Equiv.]	88266	6983	1842	1377	1915	75287	862
EP [kg Phosphate-Equiv.]	22151	2024	102	308	429	19116	173
FAETP inf. [kg DCB-Equiv.]	7287	1585	4364	396	551	0	390
GWP 100 years [kg CO2-Equiv.]	1755229	-77285561	23877660	2925340	279654	51754353	203783
HTP inf. [kg DCB-Equiv.]	267873	24363	39572	7817	10868	176594	8659
MAETP inf. [kg DCB-Equiv.]	126619498	36936978	62028408	8139989	11316619	0	8197504
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	11044	326	5936	172	240	4277	93
TETP inf. [kg DCB-Equiv.]	2354	576	1341	129	179	0	128
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.22	1.20	0.64	0.12	0.17	0.00	0.10
ADP fossil [MJ]	34728673	11134850	15924111	2400862	3337799	0	1931050
AP [kg SO2-Equiv.]	86929	6125	1535	1377	1915	75287	689
EP [kg Phosphate-Equiv.]	21817	1741	85	308	429	19116	139
FAETP inf. [kg DCB-Equiv.]	6455	1560	3637	396	551	0	312
GWP 100 years [kg CO2-Equiv.]	1643236	-77268882	23789744	2925340	279654	51754353	163027
HTP inf. [kg DCB-Equiv.]	258683	23500	32977	7817	10868	176594	6927
MAETP inf. [kg DCB-Equiv.]	113058864	35353913	51690340	8139989	11316619	0	6558003
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	10048	338	4946	172	240	4277	75
TETP inf. [kg DCB-Equiv.]	2086	557	1118	129	179	0	102

Annexure 11: LCA results – LBS 11

Paarl	∑	Primary production	Harvesting	Comminution	Forwarding	Upgrading	Secondary transport
ADP elements [kg Sb-Equiv.]	3.05	1.23	0.94	0.20	0.28	0.00	0.41
ADP fossil [MJ]	54656124	13740846	23336102	3958156	5502826	0	8118194
AP [kg SO2-Equiv.]	221811	8425	2250	2271	3157	202810	2898
EP [kg Phosphate-Equiv.]	56317	2453	124	508	706	51942	583
FAETP inf. [kg DCB-Equiv.]	10059	1857	5330	653	908	0	1312
GWP 100 years [kg CO2-Equiv.]	-29789	-130385910	39140182	4822830	461049	85246691	685369
HTP inf. [kg DCB-Equiv.]	616651	28687	48326	12888	17917	479712	29121
MAETP inf. [kg DCB-Equiv.]	178981802	43584855	75749977	13419905	18657023	0	27570041
ODP, steady state [kg R11-Equiv.]	0.05	0.04	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	21394	377	7249	284	395	12775	314
TETP inf. [kg DCB-Equiv.]	3256	678	1638	213	296	0	431
Worcester							
ADP elements [kg Sb-Equiv.]	3.15	1.36	1.10	0.20	0.28	0.00	0.22
ADP fossil [MJ]	56996539	15734426	27503263	3958156	5502826	0	4297867
AP [kg SO2-Equiv.]	222255	9832	2652	2271	3157	202810	1534
EP [kg Phosphate-Equiv.]	56486	2873	146	508	706	51942	309
FAETP inf. [kg DCB-Equiv.]	10649	2112	6282	653	908	0	695
GWP 100 years [kg CO2-Equiv.]	833723	-129314905	39255215	4822830	461049	85246691	362842
HTP inf. [kg DCB-Equiv.]	615672	32783	56956	12888	17917	479712	15417
MAETP inf. [kg DCB-Equiv.]	185848744	49899153	89276758	13419905	18657023	0	14595904
ODP, steady state [kg R11-Equiv.]	0.06	0.04	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	22587	423	8543	284	395	12775	166
TETP inf. [kg DCB-Equiv.]	3442	775	1931	213	296	0	228
Ashton							
ADP elements [kg Sb-Equiv.]	3.74	1.80	1.27	0.20	0.28	0.00	0.20
ADP fossil [MJ]	64138569	19194342	31503738	3958156	5502826	0	3979507
AP [kg SO2-Equiv.]	224208	11512	3037	2271	3157	202810	1420
EP [kg Phosphate-Equiv.]	56947	3336	168	508	706	51942	286
FAETP inf. [kg DCB-Equiv.]	12013	2614	7195	653	908	0	643
GWP 100 years [kg CO2-Equiv.]	2816172	-127416010	39365647	4822830	461049	85246691	335965
HTP inf. [kg DCB-Equiv.]	630197	40166	65241	12888	17917	479712	14275
MAETP inf. [kg DCB-Equiv.]	208749875	60895751	102262469	13419905	18657023	0	13514726
ODP, steady state [kg R11-Equiv.]	0.07	0.05	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	23932	538	9786	284	395	12775	154
TETP inf. [kg DCB-Equiv.]	3881	950	2212	213	296	0	211
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	3.68	1.98	1.05	0.20	0.28	0.00	0.18
ADP fossil [MJ]	57573414	18357351	26253115	3958156	5502826	0	3501966
AP [kg SO2-Equiv.]	222117	10098	2531	2271	3157	202810	1250
EP [kg Phosphate-Equiv.]	56419	2870	140	508	706	51942	252
FAETP inf. [kg DCB-Equiv.]	10694	2571	5996	653	908	0	566
GWP 100 years [kg CO2-Equiv.]	2658413	-127388512	39220706	4822830	461049	85246691	295649
HTP inf. [kg DCB-Equiv.]	616189	38743	54367	12888	17917	479712	12562
MAETP inf. [kg DCB-Equiv.]	187474460	58285849	85218724	13419905	18657023	0	11892959
ODP, steady state [kg R11-Equiv.]	0.06	0.05	0.01	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	22302	557	8155	284	395	12775	135
TETP inf. [kg DCB-Equiv.]	3456	918	1843	213	296	0	186

Annexure 12: LCA results – LBS 12

Paarl	∑	Prim. production	Harvesting	Comminution	Forwarding	Combustion	Upgrading	Transp. of bio-char	Transp. of bio-oil
ADP elements [kg Sb-Equiv.]	2.39	1.06	0.80	0.17	0.24	0.00	0.00	0.03	0.09
ADP fossil [MJ]	42297320	11779684	20005457	3393228	4717436	0	0	619707	1781808
AP [kg SO2-Equiv.]	187593	7223	1929	1947	2707	148246	24680	221	641
EP [kg Phosphate-Equiv.]	47721	2103	106	436	606	38171	6125	45	129
FAETP inf. [kg DCB-Equiv.]	7887	1592	4569	560	778	0	0	100	288
GWP 100 years [kg CO2-Equiv.]	-410634	-111776582	33553900	4134491	395246	69969071	3110489	52318	150433
HTP inf. [kg DCB-Equiv.]	510194	24593	41429	11048	15360	352463	56629	2223	6448
MAETP inf. [kg DCB-Equiv.]	137957256	37364207	64938562	11504549	15994200	0	0	2104574	6051163
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	18113	323	6214	244	339	9482	1418	24	70
TETP inf. [kg DCB-Equiv.]	2549	581	1404	182	254	0	0	33	95
Worcester									
ADP elements [kg Sb-Equiv.]	2.58	1.16	0.95	0.17	0.24	0.00	0.00	0.02	0.05
ADP fossil [MJ]	46448644	13488730	23577860	3393228	4717436	0	0	328080	943310
AP [kg SO2-Equiv.]	188738	8428	2273	1947	2707	148246	24680	117	339
EP [kg Phosphate-Equiv.]	48018	2463	125	436	606	38171	6125	24	68
FAETP inf. [kg DCB-Equiv.]	8739	1810	5385	560	778	0	0	53	153
GWP 100 years [kg CO2-Equiv.]	510715	-110858436	33652515	4134491	395246	69969071	3110489	27698	79641
HTP inf. [kg DCB-Equiv.]	517023	28104	48827	11048	15360	352463	56629	1177	3414
MAETP inf. [kg DCB-Equiv.]	151128523	42777297	76534734	11504549	15994200	0	0	1114186	3203557
ODP, steady state [kg R11-Equiv.]	0.05	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	19219	363	7324	244	339	9482	1418	13	37
TETP inf. [kg DCB-Equiv.]	2823	664	1655	182	254	0	0	17	50
Ashton									
ADP elements [kg Sb-Equiv.]	3.09	1.54	1.08	0.17	0.24	0.00	0.00	0.02	0.04
ADP fossil [MJ]	52750074	16454830	27007367	3393228	4717436	0	0	303778	873435
AP [kg SO2-Equiv.]	190475	9869	2604	1947	2707	148246	24680	108	314
EP [kg Phosphate-Equiv.]	48426	2860	144	436	606	38171	6125	22	63
FAETP inf. [kg DCB-Equiv.]	9937	2241	6168	560	778	0	0	49	141
GWP 100 years [kg CO2-Equiv.]	2225310	-109230561	33747186	4134491	395246	69969071	3110489	25646	73742
HTP inf. [kg DCB-Equiv.]	530114	34433	55929	11048	15360	352463	56629	1090	3161
MAETP inf. [kg DCB-Equiv.]	171368124	52204406	87667059	11504549	15994200	0	0	1031654	2966257
ODP, steady state [kg R11-Equiv.]	0.06	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	20379	461	8389	244	339	9482	1418	12	34
TETP inf. [kg DCB-Equiv.]	3209	815	1896	182	254	0	0	16	46
Rural Cederberge									
ADP elements [kg Sb-Equiv.]	3.06	1.70	0.90	0.17	0.24	0.00	0.00	0.01	0.04
ADP fossil [MJ]	47390049	15737298	22506139	3393228	4717436	0	0	267324	768623
AP [kg SO2-Equiv.]	188778	8657	2170	1947	2707	148246	24680	95	276
EP [kg Phosphate-Equiv.]	47993	2461	120	436	606	38171	6125	19	56
FAETP inf. [kg DCB-Equiv.]	8850	2204	5140	560	778	0	0	43	124
GWP 100 years [kg CO2-Equiv.]	2112702	-109206988	33622931	4134491	395246	69969071	3110489	22569	64893
HTP inf. [kg DCB-Equiv.]	519063	33214	46608	11048	15360	352463	56629	959	2782
MAETP inf. [kg DCB-Equiv.]	154039794	49967002	73055882	11504549	15994200	0	0	907855	2610306
ODP, steady state [kg R11-Equiv.]	0.05	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	18991	477	6991	244	339	9482	1418	10	30
TETP inf. [kg DCB-Equiv.]	2858	787	1580	182	254	0	0	14	41

Annexure 13: LCA results – LBS 13

Paarl	∑	Prim. production	Harvesting	Comminution	Forwarding	bio-char for sale	Combustion	Conversion	Transp. of bio-char	Transp. of bio-oil
ADP elements [kg Sb-Equiv.]	3.17	1.40	1.06	0.22	0.31	0.00	0.00	0.00	0.05	0.13
ADP fossil [MJ]	56273597	15550851	26410037	4479542	6227683	0	0	0	930389	2675095
AP [kg SO2-Equiv.]	122418	9535	2546	2570	3573	0	70317	32582	332	962
EP [kg Phosphate-Equiv.]	30685	2776	141	575	800	0	18047	8086	67	194
FAETP inf. [kg DCB-Equiv.]	10482	2101	6032	739	1027	0	0	0	150	433
GWP 100 years [kg CO2-Equiv.]	-36178053	-147560919	44295900	5458114	521780	8929400	47766987	4106287	78547	225850
HTP inf. [kg DCB-Equiv.]	376460	32466	54692	14585	20277	0	166661	74759	3337	9681
MAETP inf. [kg DCB-Equiv.]	183600901	49326045	85728099	15187634	21114609	0	0	0	3159676	9084839
ODP, steady state [kg R11-Equiv.]	0.06	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	16156	426	8204	322	447	0	4745	1871	36	105
TETP inf. [kg DCB-Equiv.]	3388	768	1854	241	335	0	0	0	49	142
Worcester										
ADP elements [kg Sb-Equiv.]	3.41	1.54	1.25	0.22	0.31	0.00	0.00	0.00	0.02	0.07
ADP fossil [MJ]	61443116	17807034	31126115	4479542	6227683	0	0	0	465194	1337548
AP [kg SO2-Equiv.]	123817	11127	3001	2570	3573	0	70317	32582	166	481
EP [kg Phosphate-Equiv.]	31056	3252	166	575	800	0	18047	8086	33	97
FAETP inf. [kg DCB-Equiv.]	11557	2390	7109	739	1027	0	0	0	75	216
GWP 100 years [kg CO2-Equiv.]	-34987983	-146348836	44426086	5458114	521780	8929400	47766987	4106287	39273	112925
HTP inf. [kg DCB-Equiv.]	384352	37101	64459	14585	20277	0	166661	74759	1669	4841
MAETP inf. [kg DCB-Equiv.]	199933278	56472090	101036688	15187634	21114609	0	0	0	1579838	4542419
ODP, steady state [kg R11-Equiv.]	0.07	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	17603	479	9669	322	447	0	4745	1871	18	52
TETP inf. [kg DCB-Equiv.]	3733	877	2185	241	335	0	0	0	25	71
Ashton										
ADP elements [kg Sb-Equiv.]	4.09	2.03	1.43	0.22	0.31	0.00	0.00	0.00	0.02	0.07
ADP fossil [MJ]	69948385	21722706	35653549	4479542	6227683	0	0	0	481236	1383670
AP [kg SO2-Equiv.]	126177	13028	3438	2570	3573	0	70317	32582	172	498
EP [kg Phosphate-Equiv.]	31608	3776	190	575	800	0	18047	8086	35	100
FAETP inf. [kg DCB-Equiv.]	13169	2958	8143	739	1027	0	0	0	78	224
GWP 100 years [kg CO2-Equiv.]	-32708731	-144199810	44551064	5458114	521780	8929400	47766987	4106287	40628	116819
HTP inf. [kg DCB-Equiv.]	402307	45456	73834	14585	20277	0	166661	74759	1726	5008
MAETP inf. [kg DCB-Equiv.]	227285755	68917209	115732933	15187634	21114609	0	0	0	1634315	4699055
ODP, steady state [kg R11-Equiv.]	0.08	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	19142	609	11075	322	447	0	4745	1871	19	54
TETP inf. [kg DCB-Equiv.]	4253	1075	2503	241	335	0	0	0	26	73
Rural Cederberge										
ADP elements [kg Sb-Equiv.]	4.04	2.24	1.19	0.22	0.31	0.00	0.00	0.00	0.02	0.05
ADP fossil [MJ]	62561576	20775462	29711291	4479542	6227683	0	0	0	352906	1014691
AP [kg SO2-Equiv.]	123826	11428	2865	2570	3573	0	70317	32582	126	365
EP [kg Phosphate-Equiv.]	31013	3248	158	575	800	0	18047	8086	25	74
FAETP inf. [kg DCB-Equiv.]	11683	2910	6786	739	1027	0	0	0	57	164
GWP 100 years [kg CO2-Equiv.]	-32883630	-144168690	44387030	5458114	521780	8929400	47766987	4106287	29794	85667
HTP inf. [kg DCB-Equiv.]	386596	43847	61529	14585	20277	0	166661	74759	1266	3672
MAETP inf. [kg DCB-Equiv.]	203354344	65963519	96444111	15187634	21114609	0	0	0	1198498	3445973
ODP, steady state [kg R11-Equiv.]	0.07	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	17298	630	9229	322	447	0	4745	1871	14	40
TETP inf. [kg DCB-Equiv.]	3773	1039	2086	241	335	0	0	0	19	54

Annexure 14: LCA results – LBS 14

Paarl	∑	Primary production	Harvesting	Forwarding	Combustion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.97	0.84	0.64	0.19	0.00	0.01	0.29
ADP fossil [MJ]	46331770	9385560	15939512	3758655	0	11411139	5836903
AP [kg SO2-Equiv.]	141572	5755	1537	2156	115926	14115	2083
EP [kg Phosphate-Equiv.]	32895	1676	85	483	29608	625	419
FAETP inf. [kg DCB-Equiv.]	8103	1268	3640	620	0	1631	943
GWP 100 years [kg CO2-Equiv.]	-202092	-89058908	26734345	314915	60120377	1194405	492774
HTP inf. [kg DCB-Equiv.]	971642	19595	33009	12238	546597	339266	20937
MAETP inf. [kg DCB-Equiv.]	3438438518	29770238	51740331	12743510	0	3324361844	19822595
ODP, steady state [kg R11-Equiv.]	0.06	0.03	0.01	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	12993	257	4951	270	6562	726	226
TETP inf. [kg DCB-Equiv.]	5971	463	1119	202	0	3877	310
Worcester							
ADP elements [kg Sb-Equiv.]	2.03	0.93	0.75	0.19	0.00	0.01	0.16
ADP fossil [MJ]	47793029	10747256	18785853	3758655	0	11411139	3090125
AP [kg SO2-Equiv.]	141826	6715	1811	2156	115926	14115	1103
EP [kg Phosphate-Equiv.]	33000	1963	100	483	29608	625	222
FAETP inf. [kg DCB-Equiv.]	8483	1442	4291	620	0	1631	499
GWP 100 years [kg CO2-Equiv.]	376127	-88327367	26812917	314915	60120377	1194405	260880
HTP inf. [kg DCB-Equiv.]	970481	22392	38903	12238	546597	339266	11084
MAETP inf. [kg DCB-Equiv.]	3442662506	34083161	60979676	12743510	0	3324361844	10494315
ODP, steady state [kg R11-Equiv.]	0.06	0.03	0.01	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	13803	289	5835	270	6562	726	119
TETP inf. [kg DCB-Equiv.]	6091	529	1319	202	0	3877	164
Ashton							
ADP elements [kg Sb-Equiv.]	2.43	1.23	0.86	0.19	0.00	0.01	0.14
ADP fossil [MJ]	52659883	13110520	21518341	3758655	0	11411139	2861227
AP [kg SO2-Equiv.]	143156	7863	2075	2156	115926	14115	1021
EP [kg Phosphate-Equiv.]	33314	2279	114	483	29608	625	206
FAETP inf. [kg DCB-Equiv.]	9413	1785	4915	620	0	1631	462
GWP 100 years [kg CO2-Equiv.]	1729255	-87030345	26888347	314915	60120377	1194405	241556
HTP inf. [kg DCB-Equiv.]	980361	27435	44562	12238	546597	339266	10263
MAETP inf. [kg DCB-Equiv.]	3458266047	41594288	69849447	12743510	0	3324361844	9716958
ODP, steady state [kg R11-Equiv.]	0.07	0.04	0.01	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	14721	368	6684	270	6562	726	111
TETP inf. [kg DCB-Equiv.]	6391	649	1511	202	0	3877	152
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.39	1.35	0.72	0.19	0.00	0.01	0.13
ADP fossil [MJ]	48158446	12538821	17931951	3758655	0	11411139	2517880
AP [kg SO2-Equiv.]	141722	6897	1729	2156	115926	14115	899
EP [kg Phosphate-Equiv.]	32952	1960	95	483	29608	625	181
FAETP inf. [kg DCB-Equiv.]	8510	1756	4096	620	0	1631	407
GWP 100 years [kg CO2-Equiv.]	1620049	-87011562	26789345	314915	60120377	1194405	212569
HTP inf. [kg DCB-Equiv.]	970731	26463	37135	12238	546597	339266	9032
MAETP inf. [kg DCB-Equiv.]	3443675768	39811618	58207873	12743510	0	3324361844	8550923
ODP, steady state [kg R11-Equiv.]	0.06	0.03	0.01	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	13607	380	5570	270	6562	726	97
TETP inf. [kg DCB-Equiv.]	6099	627	1259	202	0	3877	134

Annexure 15: LCA results – LBS 15

Paarl	∑	Primary production	Harvesting	Forwarding	Conversion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.69	0.72	0.55	0.16	0.00	0.01	0.24
ADP fossil [MJ]	39687447	8079516	13721456	3235621	0	9823227	4827626
AP [kg SO2-Equiv.]	97294	4954	1323	1856	75287	12151	1723
EP [kg Phosphate-Equiv.]	21931	1442	73	415	19116	538	347
FAETP inf. [kg DCB-Equiv.]	6944	1092	3134	534	0	1404	780
GWP 100 years [kg CO2-Equiv.]	-190606	-76665956	23014139	271093	51754353	1028198	407567
HTP inf. [kg DCB-Equiv.]	541785	16868	28416	10535	176594	292056	17317
MAETP inf. [kg DCB-Equiv.]	2959294989	25627574	44540429	10970192	0	2861761786	16395007
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	9805	222	4262	232	4277	625	187
TETP inf. [kg DCB-Equiv.]	5130	399	963	174	0	3338	256
Worcester							
ADP elements [kg Sb-Equiv.]	1.75	0.80	0.65	0.16	0.00	0.01	0.13
ADP fossil [MJ]	41043889	9251727	16171716	3235621	0	9823227	2561597
AP [kg SO2-Equiv.]	97548	5781	1559	1856	75287	12151	914
EP [kg Phosphate-Equiv.]	22029	1690	86	415	19116	538	184
FAETP inf. [kg DCB-Equiv.]	7287	1242	3693	534	0	1404	414
GWP 100 years [kg CO2-Equiv.]	315470	-76036213	23081778	271093	51754353	1028198	216260
HTP inf. [kg DCB-Equiv.]	541139	19276	33490	10535	176594	292056	9189
MAETP inf. [kg DCB-Equiv.]	2963265782	29340335	52494077	10970192	0	2861761786	8699392
ODP, steady state [kg R11-Equiv.]	0.06	0.03	0.01	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	10506	249	5023	232	4277	625	99
TETP inf. [kg DCB-Equiv.]	5238	455	1135	174	0	3338	136
Ashton							
ADP elements [kg Sb-Equiv.]	2.09	1.06	0.74	0.16	0.00	0.01	0.12
ADP fossil [MJ]	45332021	11286132	18523966	3235621	0	9823227	2463074
AP [kg SO2-Equiv.]	98728	6769	1786	1856	75287	12151	879
EP [kg Phosphate-Equiv.]	22306	1962	99	415	19116	538	177
FAETP inf. [kg DCB-Equiv.]	8103	1537	4231	534	0	1404	398
GWP 100 years [kg CO2-Equiv.]	1488621	-74919677	23146711	271093	51754353	1028198	207942
HTP inf. [kg DCB-Equiv.]	549998	23617	38361	10535	176594	292056	8835
MAETP inf. [kg DCB-Equiv.]	2977032611	35806254	60129579	10970192	0	2861761786	8364800
ODP, steady state [kg R11-Equiv.]	0.06	0.03	0.01	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	11300	316	5754	232	4277	625	95
TETP inf. [kg DCB-Equiv.]	5501	559	1300	174	0	3338	131
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.05	1.16	0.62	0.16	0.00	0.01	0.10
ADP fossil [MJ]	41259934	10793987	15436638	3235621	0	9823227	1970460
AP [kg SO2-Equiv.]	97423	5938	1488	1856	75287	12151	703
EP [kg Phosphate-Equiv.]	21981	1688	82	415	19116	538	142
FAETP inf. [kg DCB-Equiv.]	7294	1512	3526	534	0	1404	319
GWP 100 years [kg CO2-Equiv.]	1377977	-74903508	23061486	271093	51754353	1028198	166354
HTP inf. [kg DCB-Equiv.]	541001	22781	31967	10535	176594	292056	7068
MAETP inf. [kg DCB-Equiv.]	2963803451	34271650	50107983	10970192	0	2861761786	6691840
ODP, steady state [kg R11-Equiv.]	0.06	0.03	0.01	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	10333	327	4795	232	4277	625	76
TETP inf. [kg DCB-Equiv.]	5240	540	1084	174	0	3338	105

Annexure 16: LCA results – LBS 16

Paarl	∑	Primary production	Harvesting	Forwarding	Conversion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	2.80	1.20	0.91	0.27	0.00	0.01	0.42
ADP fossil [MJ]	65755141	13320208	22621732	5334373	0	16194958	8283871
AP [kg SO2-Equiv.]	239207	8167	2181	3061	202810	20032	2957
EP [kg Phosphate-Equiv.]	56608	2378	120	685	51942	887	595
FAETP inf. [kg DCB-Equiv.]	11500	1800	5167	880	0	2315	1339
GWP 100 years [kg CO2-Equiv.]	-364382	-126394505	37942013	446935	85246691	1695127	699356
HTP inf. [kg DCB-Equiv.]	1082946	27809	46847	17369	479712	481494	29715
MAETP inf. [kg DCB-Equiv.]	4879913139	42250625	73431100	18085890	0	4718012829	28132695
ODP, steady state [kg R11-Equiv.]	0.09	0.04	0.01	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	21902	365	7027	383	12775	1031	320
TETP inf. [kg DCB-Equiv.]	8475	657	1588	287	0	5503	439
Worcester							
ADP elements [kg Sb-Equiv.]	2.89	1.32	1.07	0.27	0.00	0.01	0.22
ADP fossil [MJ]	67828996	15252760	26661326	5334373	0	16194958	4385579
AP [kg SO2-Equiv.]	239569	9531	2571	3061	202810	20032	1565
EP [kg Phosphate-Equiv.]	56757	2786	142	685	51942	887	315
FAETP inf. [kg DCB-Equiv.]	12040	2047	6089	880	0	2315	709
GWP 100 years [kg CO2-Equiv.]	456241	-125356286	38053525	446935	85246691	1695127	370247
HTP inf. [kg DCB-Equiv.]	1081298	31779	55213	17369	479712	481494	15731
MAETP inf. [kg DCB-Equiv.]	4885907922	48371628	86543796	18085890	0	4718012829	14893780
ODP, steady state [kg R11-Equiv.]	0.09	0.04	0.01	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	23050	410	8282	383	12775	1031	169
TETP inf. [kg DCB-Equiv.]	8645	751	1872	287	0	5503	233
Ashton							
ADP elements [kg Sb-Equiv.]	3.45	1.74	1.23	0.27	0.00	0.01	0.20
ADP fossil [MJ]	74736150	18606760	30539338	5334373	0	16194958	4060721
AP [kg SO2-Equiv.]	241456	11160	2944	3061	202810	20032	1449
EP [kg Phosphate-Equiv.]	57203	3234	162	685	51942	887	292
FAETP inf. [kg DCB-Equiv.]	13360	2534	6975	880	0	2315	656
GWP 100 years [kg CO2-Equiv.]	2376632	-123515520	38160577	446935	85246691	1695127	342822
HTP inf. [kg DCB-Equiv.]	1095320	38936	63243	17369	479712	481494	14566
MAETP inf. [kg DCB-Equiv.]	4908052836	59031596	99131985	18085890	0	4718012829	13790537
ODP, steady state [kg R11-Equiv.]	0.10	0.05	0.01	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	24354	522	9486	383	12775	1031	157
TETP inf. [kg DCB-Equiv.]	9070	921	2144	287	0	5503	215
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	3.40	1.92	1.02	0.27	0.00	0.01	0.18
ADP fossil [MJ]	68347604	17795391	25449448	5334373	0	16194958	3573435
AP [kg SO2-Equiv.]	239420	9789	2454	3061	202810	20032	1275
EP [kg Phosphate-Equiv.]	56689	2782	135	685	51942	887	257
FAETP inf. [kg DCB-Equiv.]	12077	2492	5812	880	0	2315	578
GWP 100 years [kg CO2-Equiv.]	2221645	-123488864	38020072	446935	85246691	1695127	301683
HTP inf. [kg DCB-Equiv.]	1081653	37557	52703	17369	479712	481494	12818
MAETP inf. [kg DCB-Equiv.]	4887345967	56501588	82609987	18085890	0	4718012829	12135673
ODP, steady state [kg R11-Equiv.]	0.09	0.04	0.01	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	22772	540	7905	383	12775	1031	138
TETP inf. [kg DCB-Equiv.]	8656	890	1787	287	0	5503	190

Annexure 17: LCA results – LBS 17

Paarl	∑	Primary production	Forwarding	Comminution	Harvesting	Combustion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.31	0.61	0.14	0.19	0.10	0.00	0.27
ADP fossil [MJ]	20890744	6777362	2880467	3718612	2130619	0	5383685
AP [kg SO2-Equiv.]	126137	4156	1095	2133	906	115926	1922
EP [kg Phosphate-Equiv.]	32097	1210	225	477	191	29608	387
FAETP inf. [kg DCB-Equiv.]	3234	916	480	613	354	0	870
GWP 100 years [kg CO2-Equiv.]	1006016	-64309906	237654	3476107	1027272	60120377	454511
HTP inf. [kg DCB-Equiv.]	606393	14149	8046	12108	6182	546597	19312
MAETP inf. [kg DCB-Equiv.]	69275248	21497246	9730830	12607743	7156001	0	18283429
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7488	186	177	267	88	6562	208
TETP inf. [kg DCB-Equiv.]	1096	335	157	200	119	0	286
Worcester							
ADP elements [kg Sb-Equiv.]	1.26	0.67	0.14	0.19	0.12	0.00	0.14
ADP fossil [MJ]	19674818	7760650	2880467	3718612	2511086	0	2804003
AP [kg SO2-Equiv.]	126071	4849	1095	2133	1067	115926	1001
EP [kg Phosphate-Equiv.]	32153	1417	225	477	225	29608	201
FAETP inf. [kg DCB-Equiv.]	3006	1042	480	613	418	0	453
GWP 100 years [kg CO2-Equiv.]	1614541	-63781657	237654	3476107	1325336	60120377	236725
HTP inf. [kg DCB-Equiv.]	600263	16170	8046	12108	7286	546597	10058
MAETP inf. [kg DCB-Equiv.]	64906680	24611630	9730830	12607743	8433858	0	9522619
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7427	209	177	267	104	6562	108
TETP inf. [kg DCB-Equiv.]	1028	382	157	200	140	0	149
Ashton							
ADP elements [kg Sb-Equiv.]	1.45	0.89	0.14	0.19	0.14	0.00	0.10
ADP fossil [MJ]	20849311	9467176	2880467	3718612	2876335	0	1906722
AP [kg SO2-Equiv.]	126735	5678	1095	2133	1223	115926	681
EP [kg Phosphate-Equiv.]	32350	1645	225	477	258	29608	137
FAETP inf. [kg DCB-Equiv.]	3169	1289	480	613	478	0	308
GWP 100 years [kg CO2-Equiv.]	2405564	-62845070	237654	3476107	1255524	60120377	160973
HTP inf. [kg DCB-Equiv.]	601746	19811	8046	12108	8345	546597	6840
MAETP inf. [kg DCB-Equiv.]	68510009	30035454	9730830	12607743	9660601	0	6475381
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7464	265	177	267	119	6562	74
TETP inf. [kg DCB-Equiv.]	1088	469	157	200	161	0	101
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.52	0.98	0.14	0.19	0.11	0.00	0.10
ADP fossil [MJ]	20069255	9054349	2880467	3718612	2396946	0	2018882
AP [kg SO2-Equiv.]	125874	4981	1095	2133	1019	115926	721
EP [kg Phosphate-Equiv.]	32085	1416	225	477	215	29608	145
FAETP inf. [kg DCB-Equiv.]	3086	1268	480	613	399	0	326
GWP 100 years [kg CO2-Equiv.]	1918460	-62831507	237654	3476107	745388	60120377	170442
HTP inf. [kg DCB-Equiv.]	600056	19109	8046	12108	6955	546597	7242
MAETP inf. [kg DCB-Equiv.]	65993538	28748179	9730830	12607743	8050501	0	6856286
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7458	275	177	267	99	6562	78
TETP inf. [kg DCB-Equiv.]	1051	453	157	200	134	0	107

Annexure 18: LCA results – LBS 18

Paarl	∑	Primary production	Forwarding	Comminution	Harvesting	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.11	0.52	0.12	0.16	0.09	0.00	0.21
ADP fossil [MJ]	17597492	5834261	2479637	3201150	1834133	0	4248311
AP [kg SO2-Equiv.]	83939	3577	942	1837	780	75287	1516
EP [kg Phosphate-Equiv.]	21231	1042	193	411	164	19116	305
FAETP inf. [kg DCB-Equiv.]	2721	788	413	528	305	0	687
GWP 100 years [kg CO2-Equiv.]	833419	-55360890	204583	2992391	884323	51754353	358659
HTP inf. [kg DCB-Equiv.]	226684	12180	6926	10423	5322	176594	15239
MAETP inf. [kg DCB-Equiv.]	58323682	18505806	8376741	10853318	6160211	0	14427606
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5059	160	152	230	76	4277	164
TETP inf. [kg DCB-Equiv.]	923	288	136	172	102	0	225
Worcester							
ADP elements [kg Sb-Equiv.]	1.08	0.58	0.12	0.16	0.10	0.00	0.12
ADP fossil [MJ]	16840425	6680721	2479637	3201150	2161657	0	2317260
AP [kg SO2-Equiv.]	83986	4174	942	1837	919	75287	827
EP [kg Phosphate-Equiv.]	21300	1220	193	411	194	19116	166
FAETP inf. [kg DCB-Equiv.]	2572	897	413	528	359	0	375
GWP 100 years [kg CO2-Equiv.]	1381719	-54906149	204583	2992391	1140909	51754353	195632
HTP inf. [kg DCB-Equiv.]	222446	13919	6926	10423	6272	176594	8312
MAETP inf. [kg DCB-Equiv.]	55546721	21186810	8376741	10853318	7260248	0	7869603
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5018	180	152	230	89	4277	90
TETP inf. [kg DCB-Equiv.]	880	329	136	172	121	0	123
Ashton							
ADP elements [kg Sb-Equiv.]	1.24	0.76	0.12	0.16	0.12	0.00	0.08
ADP fossil [MJ]	17851482	8149775	2479637	3201150	2476080	0	1544840
AP [kg SO2-Equiv.]	84557	4888	942	1837	1053	75287	551
EP [kg Phosphate-Equiv.]	21469	1416	193	411	222	19116	111
FAETP inf. [kg DCB-Equiv.]	2712	1110	413	528	412	0	250
GWP 100 years [kg CO2-Equiv.]	2062668	-54099893	204583	2992391	1080812	51754353	130421
HTP inf. [kg DCB-Equiv.]	223723	17054	6926	10423	7184	176594	5541
MAETP inf. [kg DCB-Equiv.]	58648630	25855884	8376741	10853318	8316284	0	5246402
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5050	228	152	230	102	4277	60
TETP inf. [kg DCB-Equiv.]	931	403	136	172	138	0	82
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.31	0.84	0.12	0.16	0.10	0.00	0.09
ADP fossil [MJ]	17373079	7794395	2479637	3201150	2063400	0	1834498
AP [kg SO2-Equiv.]	83885	4288	942	1837	877	75287	655
EP [kg Phosphate-Equiv.]	21255	1219	193	411	185	19116	132
FAETP inf. [kg DCB-Equiv.]	2672	1092	413	528	343	0	297
GWP 100 years [kg CO2-Equiv.]	1659649	-54088217	204583	2992391	641663	51754353	154875
HTP inf. [kg DCB-Equiv.]	222960	16450	6926	10423	5987	176594	6580
MAETP inf. [kg DCB-Equiv.]	57138138	24747739	8376741	10853318	6930237	0	6230103
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5052	236	152	230	85	4277	71
TETP inf. [kg DCB-Equiv.]	910	390	136	172	115	0	97

Annexure 19: LCA results – LBS 19

Paarl	∑	Primary production	Forwarding	Comminution	Harvesting	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.85	0.86	0.20	0.26	0.14	0.00	0.38
ADP fossil [MJ]	29489457	9618592	4088026	5277541	3023824	0	7481473
AP [kg SO2-Equiv.]	217245	5898	1553	3028	1285	202810	2670
EP [kg Phosphate-Equiv.]	55464	1717	319	678	271	51942	537
FAETP inf. [kg DCB-Equiv.]	4563	1300	681	871	503	0	1209
GWP 100 years [kg CO2-Equiv.]	1336755	-91270137	337284	4933373	1457929	85246691	631614
HTP inf. [kg DCB-Equiv.]	564005	20081	11418	17184	8773	479712	26837
MAETP inf. [kg DCB-Equiv.]	97776479	30509399	13810223	17893207	10155965	0	25407685
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14083	264	251	379	125	12775	289
TETP inf. [kg DCB-Equiv.]	1548	475	223	284	169	0	397
Worcester							
ADP elements [kg Sb-Equiv.]	1.79	0.95	0.20	0.26	0.17	0.00	0.20
ADP fossil [MJ]	27922966	11014098	4088026	5277541	3563793	0	3979507
AP [kg SO2-Equiv.]	217209	6882	1553	3028	1515	202810	1420
EP [kg Phosphate-Equiv.]	55556	2011	319	678	319	51942	286
FAETP inf. [kg DCB-Equiv.]	4266	1478	681	871	593	0	643
GWP 100 years [kg CO2-Equiv.]	2213828	-90520434	337284	4933373	1880948	85246691	335965
HTP inf. [kg DCB-Equiv.]	555877	22948	11418	17184	10340	479712	14275
MAETP inf. [kg DCB-Equiv.]	92117093	34929407	13810223	17893207	11969530	0	13514726
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14002	296	251	379	147	12775	154
TETP inf. [kg DCB-Equiv.]	1459	542	223	284	199	0	211
Ashton							
ADP elements [kg Sb-Equiv.]	2.05	1.26	0.20	0.26	0.19	0.00	0.14
ADP fossil [MJ]	29589835	13436039	4088026	5277541	4082163	0	2706065
AP [kg SO2-Equiv.]	218151	8058	1553	3028	1735	202810	966
EP [kg Phosphate-Equiv.]	55834	2335	319	678	366	51942	194
FAETP inf. [kg DCB-Equiv.]	4497	1830	681	871	679	0	437
GWP 100 years [kg CO2-Equiv.]	3336466	-89191207	337284	4933373	1781869	85246691	228456
HTP inf. [kg DCB-Equiv.]	557980	28116	11418	17184	11844	479712	9707
MAETP inf. [kg DCB-Equiv.]	97231023	42627026	13810223	17893207	13710553	0	9190014
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14055	377	251	379	169	12775	105
TETP inf. [kg DCB-Equiv.]	1544	665	223	284	228	0	144
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.16	1.39	0.20	0.26	0.16	0.00	0.15
ADP fossil [MJ]	28641941	12850146	4088026	5277541	3401802	0	3024425
AP [kg SO2-Equiv.]	216985	7069	1553	3028	1446	202810	1079
EP [kg Phosphate-Equiv.]	55470	2009	319	678	305	51942	217
FAETP inf. [kg DCB-Equiv.]	4406	1800	681	871	566	0	489
GWP 100 years [kg CO2-Equiv.]	2658595	-89171958	337284	4933373	1057872	85246691	255333
HTP inf. [kg DCB-Equiv.]	556153	27120	11418	17184	9870	479712	10849
MAETP inf. [kg DCB-Equiv.]	94200177	40800094	13810223	17893207	11425461	0	10271192
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14053	390	251	379	141	12775	117
TETP inf. [kg DCB-Equiv.]	1500	643	223	284	190	0	160

Annexure 20: LCA results – LBS 20

Paarl	∑	Prim. production	Forwarding	Comminution	Harvesting	Combustion	Conversion	transport of bio-char	transport of bio-oil
ADP elements [kg Sb-Equiv.]	1.37	0.74	0.17	0.23	0.12	0.00	0.00	0.03	0.08
ADP fossil [MJ]	21079942	8245734	3504544	4524280	2592235	0	0	571099	1642049
AP [kg SO2-Equiv.]	183806	5056	1332	2596	1102	148246	24680	204	591
EP [kg Phosphate-Equiv.]	47015	1472	273	581	232	38171	6125	41	119
FAETP inf. [kg DCB-Equiv.]	3233	1114	584	746	431	0	0	92	265
GWP 100 years [kg CO2-Equiv.]	791423	-78243187	289143	4229235	1249840	69969071	3110473	48214	138633
HTP inf. [kg DCB-Equiv.]	466339	17215	9789	14731	7521	352463	56629	2049	5943
MAETP inf. [kg DCB-Equiv.]	69555656	26154804	11839096	15339317	8706408	0	0	1939499	5576532
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	11860	226	215	325	107	9482	1418	22	64
TETP inf. [kg DCB-Equiv.]	1104	407	192	243	145	0	0	30	87
Worcester									
ADP elements [kg Sb-Equiv.]	1.42	0.82	0.17	0.23	0.15	0.00	0.00	0.02	0.04
ADP fossil [MJ]	21703225	9442060	3504544	4524280	3055134	0	0	303776	873431
AP [kg SO2-Equiv.]	184475	5900	1332	2596	1299	148246	24680	108	314
EP [kg Phosphate-Equiv.]	47234	1724	273	581	274	38171	6125	22	63
FAETP inf. [kg DCB-Equiv.]	3296	1267	584	746	508	0	0	49	141
GWP 100 years [kg CO2-Equiv.]	1709302	-77600488	289143	4229235	1612481	69969071	3110473	25646	73741
HTP inf. [kg DCB-Equiv.]	466399	19673	9789	14731	8864	352463	56629	1090	3161
MAETP inf. [kg DCB-Equiv.]	71381372	29943946	11839096	15339317	10261124	0	0	1031648	2966241
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	11866	254	215	325	126	9482	1418	12	34
TETP inf. [kg DCB-Equiv.]	1133	465	192	243	170	0	0	16	46
Ashton									
ADP elements [kg Sb-Equiv.]	1.68	1.08	0.17	0.23	0.17	0.00	0.00	0.01	0.03
ADP fossil [MJ]	23847161	11518319	3504544	4524280	3499517	0	0	206568	593933
AP [kg SO2-Equiv.]	185537	6908	1332	2596	1488	148246	24680	74	214
EP [kg Phosphate-Equiv.]	47524	2002	273	581	314	38171	6125	15	43
FAETP inf. [kg DCB-Equiv.]	3610	1569	584	746	582	0	0	33	96
GWP 100 years [kg CO2-Equiv.]	2732067	-76460982	289143	4229235	1527544	69969071	3110473	17439	50144
HTP inf. [kg DCB-Equiv.]	470759	24103	9789	14731	10154	352463	56629	741	2149
MAETP inf. [kg DCB-Equiv.]	78193515	36542888	11839096	15339317	11753651	0	0	701521	2017044
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	11939	323	215	325	145	9482	1418	8	23
TETP inf. [kg DCB-Equiv.]	1243	570	192	243	195	0	0	11	32
Rural Cederberge									
ADP elements [kg Sb-Equiv.]	1.77	1.19	0.17	0.23	0.14	0.00	0.00	0.01	0.03
ADP fossil [MJ]	22855815	11016049	3504544	4524280	2916264	0	0	230870	663807
AP [kg SO2-Equiv.]	184474	6060	1332	2596	1240	148246	24680	82	239
EP [kg Phosphate-Equiv.]	47199	1722	273	581	261	38171	6125	17	48
FAETP inf. [kg DCB-Equiv.]	3502	1543	584	746	485	0	0	37	107
GWP 100 years [kg CO2-Equiv.]	2135858	-76444480	289143	4229235	906882	69969071	3110473	19491	56043
HTP inf. [kg DCB-Equiv.]	468553	23249	9789	14731	8461	352463	56629	828	2402
MAETP inf. [kg DCB-Equiv.]	74988230	34976713	11839096	15339317	9794709	0	0	784053	2254343
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	11930	334	215	325	121	9482	1418	9	26
TETP inf. [kg DCB-Equiv.]	1196	551	192	243	163	0	0	12	35

Annexure 21: LCA results – LBS 21

Paarl	∑	Prim. production	Forwarding	Comminution	Harvesting	bio-char for sale	Combustion	Upgrading	transport	transport
ADP elements [kg Sb-Equiv.]	1.81	0.98	0.23	0.30	0.16	0.00	0.00	0.00	0.04	0.11
ADP fossil [MJ]	27828659	10885596	4626519	5972722	3422136	0	0	0	753936	2167749
AP [kg SO2-Equiv.]	117262	6675	1758	3427	1455	0	70317	32582	269	780
EP [kg Phosphate-Equiv.]	29722	1943	361	767	307	0	18047	8086	54	157
FAETP inf. [kg DCB-Equiv.]	4268	1471	771	985	569	0	0	0	122	350
GWP 100 years [kg CO2-Equiv.]	-34628397	-103292643	381712	5583219	1649974	8929400	47766987	4106287	63650	183017
HTP inf. [kg DCB-Equiv.]	316995	22726	12923	19447	9929	0	166661	74759	2704	7845
MAETP inf. [kg DCB-Equiv.]	91823810	34528231	15629367	20250179	11493754	0	0	0	2560427	7361852
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7884	298	284	429	141	0	4745	1871	29	85
TETP inf. [kg DCB-Equiv.]	1457	537	253	321	191	0	0	0	40	115
Worcester									**of bio-char**	**Of bio-oil**
ADP elements [kg Sb-Equiv.]	1.87	1.08	0.23	0.30	0.19	0.00	0.00	0.00	0.02	0.06
ADP fossil [MJ]	28651485	12464924	4626519	5972722	4033231	0	0	0	401030	1153058
AP [kg SO2-Equiv.]	118145	7789	1758	3427	1715	0	70317	32582	143	415
EP [kg Phosphate-Equiv.]	30011	2276	361	767	361	0	18047	8086	29	84
FAETP inf. [kg DCB-Equiv.]	4351	1673	771	985	671	0	0	0	65	186
GWP 100 years [kg CO2-Equiv.]	-33416660	-102444185	381712	5583219	2128715	8929400	47766987	4106287	33856	97349
HTP inf. [kg DCB-Equiv.]	317074	25971	12923	19447	11702	0	166661	74759	1439	4173
MAETP inf. [kg DCB-Equiv.]	94234027	39530463	15629367	20250179	13546210	0	0	0	1361929	3915879
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7892	335	284	429	167	0	4745	1871	15	45
TETP inf. [kg DCB-Equiv.]	1495	614	253	321	225	0	0	0	21	61
Ashton										
ADP elements [kg Sb-Equiv.]	2.22	1.42	0.23	0.30	0.22	0.00	0.00	0.00	0.01	0.04
ADP fossil [MJ]	31481799	15205894	4626519	5972722	4619883	0	0	0	272700	784080
AP [kg SO2-Equiv.]	119547	9120	1758	3427	1964	0	70317	32582	97	282
EP [kg Phosphate-Equiv.]	30394	2643	361	767	414	0	18047	8086	20	57
FAETP inf. [kg DCB-Equiv.]	4766	2071	771	985	768	0	0	0	44	127
GWP 100 years [kg CO2-Equiv.]	-32066458	-100939867	381712	5583219	2016585	8929400	47766987	4106287	23022	66198
HTP inf. [kg DCB-Equiv.]	322829	31820	12923	19447	13404	0	166661	74759	978	2838
MAETP inf. [kg DCB-Equiv.]	103227069	48242046	15629367	20250179	15516567	0	0	0	926112	2662798
ODP, steady state [kg R11-Equiv.]	0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7988	426	284	429	191	0	4745	1871	11	31
TETP inf. [kg DCB-Equiv.]	1641	753	253	321	258	0	0	0	14	42
Rural Cederberge										
ADP elements [kg Sb-Equiv.]	2.34	1.57	0.23	0.30	0.18	0.00	0.00	0.00	0.02	0.04
ADP fossil [MJ]	30173075	14542824	4626519	5972722	3849903	0	0	0	304783	876324
AP [kg SO2-Equiv.]	118144	8000	1758	3427	1637	0	70317	32582	109	315
EP [kg Phosphate-Equiv.]	29965	2274	361	767	345	0	18047	8086	22	64
FAETP inf. [kg DCB-Equiv.]	4624	2037	771	985	640	0	0	0	49	142
GWP 100 years [kg CO2-Equiv.]	-32853542	-100918083	381712	5583219	1197219	8929400	47766987	4106287	25731	73986
HTP inf. [kg DCB-Equiv.]	319917	30693	12923	19447	11170	0	166661	74759	1093	3171
MAETP inf. [kg DCB-Equiv.]	98995616	46174463	15629367	20250179	12930473	0	0	0	1035066	2976068
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7976	441	284	429	159	0	4745	1871	12	34
TETP inf. [kg DCB-Equiv.]	1579	728	253	321	215	0	0	0	16	46

Annexure 22: LCA results – LBS 22

Paarl	∑	Primary production	Forwarding	Harvesting	Combustion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.11	0.59	0.14	0.10	0.00	0.01	0.28
ADP fossil [MJ]	28332272	6569892	2792289	2065396	0	11411139	5493556
AP [kg SO2-Equiv.]	137969	4028	1061	878	115926	14115	1961
EP [kg Phosphate-Equiv.]	32203	1173	218	185	29608	625	395
FAETP inf. [kg DCB-Equiv.]	4215	888	465	343	0	1631	888
GWP 100 years [kg CO2-Equiv.]	663537	-62341235	230379	995825	60120377	1194405	463787
HTP inf. [kg DCB-Equiv.]	933077	13716	7799	5993	546597	339266	19706
MAETP inf. [kg DCB-Equiv.]	3380227457	20839167	9432947	6936939	0	3324361844	18656560
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	7938	180	172	85	6562	726	212
TETP inf. [kg DCB-Equiv.]	4761	324	153	115	0	3877	291
Worcester							
ADP elements [kg Sb-Equiv.]	1.05	0.65	0.14	0.12	0.00	0.01	0.14
ADP fossil [MJ]	27021951	7523079	2792289	2434216	0	11411139	2861227
AP [kg SO2-Equiv.]	137858	4701	1061	1035	115926	14115	1021
EP [kg Phosphate-Equiv.]	32248	1374	218	218	29608	625	206
FAETP inf. [kg DCB-Equiv.]	3973	1010	465	405	0	1631	462
GWP 100 years [kg CO2-Equiv.]	1242323	-61829157	230379	1284764	60120377	1194405	241556
HTP inf. [kg DCB-Equiv.]	926663	15675	7799	7063	546597	339266	10263
MAETP inf. [kg DCB-Equiv.]	3375545641	23858213	9432947	8175678	0	3324361844	9716958
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	7874	202	172	101	6562	726	111
TETP inf. [kg DCB-Equiv.]	4688	370	153	136	0	3877	152
Ashton							
ADP elements [kg Sb-Equiv.]	1.23	0.86	0.14	0.13	0.00	0.01	0.10
ADP fossil [MJ]	28114711	9177364	2792289	2788284	0	11411139	1945634
AP [kg SO2-Equiv.]	138485	5504	1061	1185	115926	14115	694
EP [kg Phosphate-Equiv.]	32435	1595	218	250	29608	625	140
FAETP inf. [kg DCB-Equiv.]	4124	1250	465	464	0	1631	314
GWP 100 years [kg CO2-Equiv.]	2005266	-60921241	230379	1217089	60120377	1194405	164258
HTP inf. [kg DCB-Equiv.]	927935	19204	7799	8090	546597	339266	6979
MAETP inf. [kg DCB-Equiv.]	3378883192	29116002	9432947	9364868	0	3324361844	6607532
ODP, steady state [kg R11-Equiv.]	0.05	0.03	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	7908	257	172	115	6562	726	75
TETP inf. [kg DCB-Equiv.]	4743	454	153	156	0	3877	103
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.30	0.95	0.14	0.11	0.00	0.01	0.10
ADP fossil [MJ]	27364257	8777175	2792289	2323570	0	11411139	2060084
AP [kg SO2-Equiv.]	137653	4828	1061	988	115926	14115	735
EP [kg Phosphate-Equiv.]	32179	1372	218	208	29608	625	148
FAETP inf. [kg DCB-Equiv.]	4045	1229	465	386	0	1631	333
GWP 100 years [kg CO2-Equiv.]	1533557	-60908093	230379	722570	60120377	1194405	173920
HTP inf. [kg DCB-Equiv.]	926318	18524	7799	6742	546597	339266	7390
MAETP inf. [kg DCB-Equiv.]	3376463190	27868133	9432947	7804057	0	3324361844	6996210
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	7902	266	172	96	6562	726	80
TETP inf. [kg DCB-Equiv.]	4708	439	153	130	0	3877	109

Annexure 23: LCA results – LBS 23

Paarl	∑	Primary production	Forwarding	Harvesting	Conversion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	0.95	0.51	0.12	0.08	0.00	0.01	0.24
ADP fossil [MJ]	24389707	5655662	2403729	1777986	0	9823227	4729103
AP [kg SO2-Equiv.]	94262	3468	913	756	75287	12151	1688
EP [kg Phosphate-Equiv.]	21350	1010	187	159	19116	538	340
FAETP inf. [kg DCB-Equiv.]	3629	764	400	296	0	1404	764
GWP 100 years [kg CO2-Equiv.]	571203	-53666169	198320	857252	51754353	1028198	399249
HTP inf. [kg DCB-Equiv.]	509294	11808	6714	5159	176594	292056	16964
MAETP inf. [kg DCB-Equiv.]	2909853446	17939302	8120310	5971633	0	2861761786	16060415
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	5461	155	148	73	4277	625	183
TETP inf. [kg DCB-Equiv.]	4098	279	131	99	0	3338	251
Worcester							
ADP elements [kg Sb-Equiv.]	0.91	0.56	0.12	0.10	0.00	0.01	0.12
ADP fossil [MJ]	23261724	6476209	2403729	2095484	0	9823227	2463074
AP [kg SO2-Equiv.]	94167	4047	913	891	75287	12151	879
EP [kg Phosphate-Equiv.]	21389	1183	187	188	19116	538	177
FAETP inf. [kg DCB-Equiv.]	3420	869	400	348	0	1404	398
GWP 100 years [kg CO2-Equiv.]	1069448	-53225349	198320	1105984	51754353	1028198	207942
HTP inf. [kg DCB-Equiv.]	503772	13493	6714	6080	176594	292056	8835
MAETP inf. [kg DCB-Equiv.]	2905823125	20538234	8120310	7037996	0	2861761786	8364800
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	5406	174	148	87	4277	625	95
TETP inf. [kg DCB-Equiv.]	4036	319	131	117	0	3338	131
Ashton							
ADP elements [kg Sb-Equiv.]	1.06	0.74	0.12	0.11	0.00	0.01	0.08
ADP fossil [MJ]	24202421	7900292	2403729	2400282	0	9823227	1674891
AP [kg SO2-Equiv.]	94707	4738	913	1020	75287	12151	598
EP [kg Phosphate-Equiv.]	21550	1373	187	215	19116	538	120
FAETP inf. [kg DCB-Equiv.]	3550	1076	400	399	0	1404	271
GWP 100 years [kg CO2-Equiv.]	1726225	-52443774	198320	1047726	51754353	1028198	141401
HTP inf. [kg DCB-Equiv.]	504868	16532	6714	6964	176594	292056	6008
MAETP inf. [kg DCB-Equiv.]	2908696241	25064378	8120310	8061704	0	2861761786	5688064
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	5435	222	148	99	4277	625	65
TETP inf. [kg DCB-Equiv.]	4083	391	131	134	0	3338	89
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.12	0.81	0.12	0.10	0.00	0.01	0.09
ADP fossil [MJ]	23556396	7555791	2403729	2000235	0	9823227	1773414
AP [kg SO2-Equiv.]	93990	4156	913	850	75287	12151	633
EP [kg Phosphate-Equiv.]	21329	1181	187	179	19116	538	127
FAETP inf. [kg DCB-Equiv.]	3482	1058	400	333	0	1404	287
GWP 100 years [kg CO2-Equiv.]	1320155	-52432455	198320	622021	51754353	1028198	149718
HTP inf. [kg DCB-Equiv.]	503475	15947	6714	5803	176594	292056	6361
MAETP inf. [kg DCB-Equiv.]	2906612994	23990155	8120310	6718087	0	2861761786	6022656
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	5430	229	148	83	4277	625	69
TETP inf. [kg DCB-Equiv.]	4053	378	131	112	0	3338	94

Annexure 24: LCA results – LBS 24

Paarl	∑	Primary production	Forwarding	Harvesting	Conversion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.57	0.84	0.19	0.14	0.00	0.01	0.39
ADP fossil [MJ]	40209829	9324146	3962883	2931258	0	16194958	7796585
AP [kg SO2-Equiv.]	234094	5717	1506	1246	202810	20032	2783
EP [kg Phosphate-Equiv.]	55626	1665	309	263	51942	887	560
FAETP inf. [kg DCB-Equiv.]	5982	1260	660	487	0	2315	1260
GWP 100 years [kg CO2-Equiv.]	864140	-88476153	326959	1413299	85246691	1695127	658217
HTP inf. [kg DCB-Equiv.]	1028213	19466	11069	8505	479712	481494	27967
MAETP inf. [kg DCB-Equiv.]	4797298626	29575437	13387461	9845068	0	4718012829	26477831
ODP, steady state [kg R11-Equiv.]	0.06698	0.02607	0.00138	0.00104	0.00000	0.03582	0.00266
POCP [kg Ethene-Equiv.]	14728	256	244	121	12775	1031	301
TETP inf. [kg DCB-Equiv.]	6757	460	217	164	0	5503	414
Worcester							
ADP elements [kg Sb-Equiv.]	1.50	0.92	0.19	0.16	0.00	0.01	0.20
ADP fossil [MJ]	38350191	10676932	3962883	3454697	0	16194958	4060721
AP [kg SO2-Equiv.]	233937	6671	1506	1469	202810	20032	1449
EP [kg Phosphate-Equiv.]	55690	1950	309	310	51942	887	292
FAETP inf. [kg DCB-Equiv.]	5639	1433	660	575	0	2315	656
GWP 100 years [kg CO2-Equiv.]	1685567	-87749400	326959	1823368	85246691	1695127	342822
HTP inf. [kg DCB-Equiv.]	1019110	22246	11069	10023	479712	481494	14566
MAETP inf. [kg DCB-Equiv.]	4790654082	33860139	13387461	11603116	0	4718012829	13790537
ODP, steady state [kg R11-Equiv.]	0.07	0.03	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	14636	287	244	143	12775	1031	157
TETP inf. [kg DCB-Equiv.]	6653	526	217	193	0	5503	215
Ashton							
ADP elements [kg Sb-Equiv.]	1.75	1.22	0.19	0.19	0.00	0.01	0.14
ADP fossil [MJ]	39901062	13024732	3962883	3957199	0	16194958	2761290
AP [kg SO2-Equiv.]	234827	7812	1506	1682	202810	20032	986
EP [kg Phosphate-Equiv.]	55955	2264	309	355	51942	887	198
FAETP inf. [kg DCB-Equiv.]	5853	1774	660	658	0	2315	446
GWP 100 years [kg CO2-Equiv.]	2768354	-86460864	326959	1727322	85246691	1695127	233119
HTP inf. [kg DCB-Equiv.]	1020916	27255	11069	11481	479712	481494	9905
MAETP inf. [kg DCB-Equiv.]	4795390814	41322117	13387461	13290842	0	4718012829	9377565
ODP, steady state [kg R11-Equiv.]	0.08	0.04	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	14685	365	244	164	12775	1031	107
TETP inf. [kg DCB-Equiv.]	6732	645	217	221	0	5503	146
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.85	1.34	0.19	0.16	0.00	0.01	0.15
ADP fossil [MJ]	38835999	12456774	3962883	3297665	0	16194958	2923719
AP [kg SO2-Equiv.]	233645	6852	1506	1402	202810	20032	1044
EP [kg Phosphate-Equiv.]	55592	1948	309	296	51942	887	210
FAETP inf. [kg DCB-Equiv.]	5740	1745	660	548	0	2315	473
GWP 100 years [kg CO2-Equiv.]	2098892	-86442205	326959	1025488	85246691	1695127	246831
HTP inf. [kg DCB-Equiv.]	1018620	26290	11069	9568	479712	481494	10488
MAETP inf. [kg DCB-Equiv.]	4791956290	39551112	13387461	11075702	0	4718012829	9929187
ODP, steady state [kg R11-Equiv.]	0.07	0.03	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	14677	378	244	136	12775	1031	113
TETP inf. [kg DCB-Equiv.]	6682	623	217	184	0	5503	155

Annexure 25: LCA results – LBS 25

Paarl	∑	Primary production	Comminution	Forwarding	Harvesting	Combustion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.46	0.61	0.19	0.29	0.10	0.00	0.27
ADP fossil [MJ]	23818016	6777362	3718612	5807739	2130619	0	5383685
AP [kg SO2-Equiv.]	128384	4156	2133	3342	906	115926	1922
EP [kg Phosphate-Equiv.]	32621	1210	477	748	191	29608	387
FAETP inf. [kg DCB-Equiv.]	3713	916	613	959	354	0	870
GWP 100 years [kg CO2-Equiv.]	1254870	-64309906	3476107	486508	1027272	60120377	454511
HTP inf. [kg DCB-Equiv.]	617282	14149	12108	18935	6182	546597	19312
MAETP inf. [kg DCB-Equiv.]	79234390	21497246	12607743	19689972	7156001	0	18283429
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7737	186	267	425	88	6562	208
TETP inf. [kg DCB-Equiv.]	1251	335	200	312	119	0	286
Worcester							
ADP elements [kg Sb-Equiv.]	1.41	0.67	0.19	0.29	0.12	0.00	0.14
ADP fossil [MJ]	22602089	7760650	3718612	5807739	2511086	0	2804003
AP [kg SO2-Equiv.]	128318	4849	2133	3342	1067	115926	1001
EP [kg Phosphate-Equiv.]	32677	1417	477	748	225	29608	201
FAETP inf. [kg DCB-Equiv.]	3485	1042	613	959	418	0	453
GWP 100 years [kg CO2-Equiv.]	1863396	-63781657	3476107	486508	1325336	60120377	236725
HTP inf. [kg DCB-Equiv.]	611153	16170	12108	18935	7286	546597	10058
MAETP inf. [kg DCB-Equiv.]	74865822	24611630	12607743	19689972	8433858	0	9522619
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7675	209	267	425	104	6562	108
TETP inf. [kg DCB-Equiv.]	1183	382	200	312	140	0	149
Ashton							
ADP elements [kg Sb-Equiv.]	1.60	0.89	0.19	0.29	0.14	0.00	0.10
ADP fossil [MJ]	23776583	9467176	3718612	5807739	2876335	0	1906722
AP [kg SO2-Equiv.]	128982	5678	2133	3342	1223	115926	681
EP [kg Phosphate-Equiv.]	32873	1645	477	748	258	29608	137
FAETP inf. [kg DCB-Equiv.]	3648	1289	613	959	478	0	308
GWP 100 years [kg CO2-Equiv.]	2654419	-62845070	3476107	486508	1255524	60120377	160973
HTP inf. [kg DCB-Equiv.]	612635	19811	12108	18935	8345	546597	6840
MAETP inf. [kg DCB-Equiv.]	78469151	30035454	12607743	19689972	9660601	0	6475381
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7713	265	267	425	119	6562	74
TETP inf. [kg DCB-Equiv.]	1243	469	200	312	161	0	101
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.67	0.98	0.19	0.29	0.11	0.00	0.10
ADP fossil [MJ]	22996527	9054349	3718612	5807739	2396946	0	2018882
AP [kg SO2-Equiv.]	128121	4981	2133	3342	1019	115926	721
EP [kg Phosphate-Equiv.]	32609	1416	477	748	215	29608	145
FAETP inf. [kg DCB-Equiv.]	3566	1268	613	959	399	0	326
GWP 100 years [kg CO2-Equiv.]	2167314	-62831507	3476107	486508	745388	60120377	170442
HTP inf. [kg DCB-Equiv.]	610945	19109	12108	18935	6955	546597	7242
MAETP inf. [kg DCB-Equiv.]	75952680	28748179	12607743	19689972	8050501	0	6856286
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7706	275	267	425	99	6562	78
TETP inf. [kg DCB-Equiv.]	1206	453	200	312	134	0	107

Annexure 26: LCA results – LBS 26

Paarl	∑	Primary production	Comminution	Forwarding	Harvesting	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.24	0.52	0.16	0.25	0.09	0.00	0.21
ADP fossil [MJ]	20117421	5834261	3201150	4999565	1834133	0	4248311
AP [kg SO2-Equiv.]	85873	3577	1837	2877	780	75287	1516
EP [kg Phosphate-Equiv.]	21682	1042	411	644	164	19116	305
FAETP inf. [kg DCB-Equiv.]	3134	788	528	826	305	0	687
GWP 100 years [kg CO2-Equiv.]	1047644	-55360890	2992391	418808	884323	51754353	358659
HTP inf. [kg DCB-Equiv.]	236058	12180	10423	16300	5322	176594	15239
MAETP inf. [kg DCB-Equiv.]	66896964	18505806	10853318	16950023	6160211	0	14427606
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5273	160	230	366	76	4277	164
TETP inf. [kg DCB-Equiv.]	1057	288	172	269	102	0	225
Worcester							
ADP elements [kg Sb-Equiv.]	1.21	0.58	0.16	0.25	0.10	0.00	0.12
ADP fossil [MJ]	19360353	6680721	3201150	4999565	2161657	0	2317260
AP [kg SO2-Equiv.]	85920	4174	1837	2877	919	75287	827
EP [kg Phosphate-Equiv.]	21751	1220	411	644	194	19116	166
FAETP inf. [kg DCB-Equiv.]	2985	897	528	826	359	0	375
GWP 100 years [kg CO2-Equiv.]	1595944	-54906149	2992391	418808	1140909	51754353	195632
HTP inf. [kg DCB-Equiv.]	231820	13919	10423	16300	6272	176594	8312
MAETP inf. [kg DCB-Equiv.]	64120003	21186810	10853318	16950023	7260248	0	7869603
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5231	180	230	366	89	4277	90
TETP inf. [kg DCB-Equiv.]	1014	329	172	269	121	0	123
Ashton							
ADP elements [kg Sb-Equiv.]	1.37	0.76	0.16	0.25	0.12	0.00	0.08
ADP fossil [MJ]	20371411	8149775	3201150	4999565	2476080	0	1544840
AP [kg SO2-Equiv.]	86492	4888	1837	2877	1053	75287	551
EP [kg Phosphate-Equiv.]	21920	1416	411	644	222	19116	111
FAETP inf. [kg DCB-Equiv.]	3125	1110	528	826	412	0	250
GWP 100 years [kg CO2-Equiv.]	2276893	-54099893	2992391	418808	1080812	51754353	130421
HTP inf. [kg DCB-Equiv.]	233097	17054	10423	16300	7184	176594	5541
MAETP inf. [kg DCB-Equiv.]	67221912	25855884	10853318	16950023	8316284	0	5246402
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5263	228	230	366	102	4277	60
TETP inf. [kg DCB-Equiv.]	1065	403	172	269	138	0	82
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.44	0.84	0.16	0.25	0.10	0.00	0.09
ADP fossil [MJ]	19893008	7794395	3201150	4999565	2063400	0	1834498
AP [kg SO2-Equiv.]	85819	4288	1837	2877	877	75287	655
EP [kg Phosphate-Equiv.]	21706	1219	411	644	185	19116	132
FAETP inf. [kg DCB-Equiv.]	3085	1092	528	826	343	0	297
GWP 100 years [kg CO2-Equiv.]	1873874	-54088217	2992391	418808	641663	51754353	154875
HTP inf. [kg DCB-Equiv.]	232334	16450	10423	16300	5987	176594	6580
MAETP inf. [kg DCB-Equiv.]	65711420	24747739	10853318	16950023	6930237	0	6230103
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5265	236	230	366	85	4277	71
TETP inf. [kg DCB-Equiv.]	1044	390	172	269	115	0	97

Annexure 27: LCA results – LBS 27

Paarl	∑	Primary production	Comminution	Forwarding	Harvesting	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	2.06	0.86	0.26	0.41	0.14	0.00	0.38
ADP fossil [MJ]	33643910	9618592	5277541	8242480	3023824	0	7481473
AP [kg SO2-Equiv.]	220434	5898	3028	4743	1285	202810	2670
EP [kg Phosphate-Equiv.]	56207	1717	678	1062	271	51942	537
FAETP inf. [kg DCB-Equiv.]	5244	1300	871	1361	503	0	1209
GWP 100 years [kg CO2-Equiv.]	1689935	-91270137	4933373	690463	1457929	85246691	631614
HTP inf. [kg DCB-Equiv.]	579459	20081	17184	26873	8773	479712	26837
MAETP inf. [kg DCB-Equiv.]	111910728	30509399	17893207	27944473	10155965	0	25407685
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14435	264	379	603	125	12775	289
TETP inf. [kg DCB-Equiv.]	1768	475	284	443	169	0	397
Worcester							
ADP elements [kg Sb-Equiv.]	2.00	0.95	0.26	0.41	0.17	0.00	0.20
ADP fossil [MJ]	32077419	11014098	5277541	8242480	3563793	0	3979507
AP [kg SO2-Equiv.]	220398	6882	3028	4743	1515	202810	1420
EP [kg Phosphate-Equiv.]	56299	2011	678	1062	319	51942	286
FAETP inf. [kg DCB-Equiv.]	4946	1478	871	1361	593	0	643
GWP 100 years [kg CO2-Equiv.]	2567007	-90520434	4933373	690463	1880948	85246691	335965
HTP inf. [kg DCB-Equiv.]	571331	22948	17184	26873	10340	479712	14275
MAETP inf. [kg DCB-Equiv.]	106251343	34929407	17893207	27944473	11969530	0	13514726
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14355	296	379	603	147	12775	154
TETP inf. [kg DCB-Equiv.]	1679	542	284	443	199	0	211
Ashton							
ADP elements [kg Sb-Equiv.]	2.26	1.26	0.26	0.41	0.19	0.00	0.14
ADP fossil [MJ]	33744288	13436039	5277541	8242480	4082163	0	2706065
AP [kg SO2-Equiv.]	221340	8058	3028	4743	1735	202810	966
EP [kg Phosphate-Equiv.]	56577	2335	678	1062	366	51942	194
FAETP inf. [kg DCB-Equiv.]	5178	1830	871	1361	679	0	437
GWP 100 years [kg CO2-Equiv.]	3689646	-89191207	4933373	690463	1781869	85246691	228456
HTP inf. [kg DCB-Equiv.]	573435	28116	17184	26873	11844	479712	9707
MAETP inf. [kg DCB-Equiv.]	111365272	42627026	17893207	27944473	13710553	0	9190014
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14407	377	379	603	169	12775	105
TETP inf. [kg DCB-Equiv.]	1764	665	284	443	228	0	144
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.38	1.39	0.26	0.41	0.16	0.00	0.15
ADP fossil [MJ]	32796394	12850146	5277541	8242480	3401802	0	3024425
AP [kg SO2-Equiv.]	220175	7069	3028	4743	1446	202810	1079
EP [kg Phosphate-Equiv.]	56213	2009	678	1062	305	51942	217
FAETP inf. [kg DCB-Equiv.]	5086	1800	871	1361	566	0	489
GWP 100 years [kg CO2-Equiv.]	3011775	-89171958	4933373	690463	1057872	85246691	255333
HTP inf. [kg DCB-Equiv.]	571607	27120	17184	26873	9870	479712	10849
MAETP inf. [kg DCB-Equiv.]	108334426	40800094	17893207	27944473	11425461	0	10271192
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14405	390	379	603	141	12775	117
TETP inf. [kg DCB-Equiv.]	1720	643	284	443	190	0	160

Annexure 28: LCA results – LBS 28

Paarl	∑	Prim .production	Comminution	Forwarding	Harvesting	Combustion	Conversion	Transp. of bio-char	Transp. of bio-oil
ADP elements [kg Sb-Equiv.]	1.55	0.74	0.23	0.35	0.12	0.00	0.00	0.03	0.08
ADP fossil [MJ]	24641564	8245779	4524304	7066072	2592249	0	0	571102	1642058
AP [kg SO2-Equiv.]	186540	5056	2596	4066	1102	148246	24680	204	591
EP [kg Phosphate-Equiv.]	47652	1472	581	910	232	38171	6125	41	119
FAETP inf. [kg DCB-Equiv.]	3817	1114	746	1167	431	0	0	92	265
GWP 100 years [kg CO2-Equiv.]	1093823	-78243608	4229258	591917	1249846	69969071	3110489	48215	138634
HTP inf. [kg DCB-Equiv.]	479588	17215	14731	23037	7521	352463	56629	2049	5943
MAETP inf. [kg DCB-Equiv.]	81672969	26154945	15339399	23956098	8706455	0	0	1939509	5576562
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	12162	226	325	517	107	9482	1418	22	64
TETP inf. [kg DCB-Equiv.]	1292	407	243	380	145	0	0	30	87
Worcester									
ADP elements [kg Sb-Equiv.]	1.60	0.82	0.23	0.35	0.15	0.00	0.00	0.02	0.04
ADP fossil [MJ]	25264851	9442111	4524304	7066072	3055151	0	0	303778	873435
AP [kg SO2-Equiv.]	187209	5900	2596	4066	1299	148246	24680	108	314
EP [kg Phosphate-Equiv.]	47871	1724	581	910	274	38171	6125	22	63
FAETP inf. [kg DCB-Equiv.]	3879	1267	746	1167	508	0	0	49	141
GWP 100 years [kg CO2-Equiv.]	2011707	-77600906	4229258	591917	1612490	69969071	3110489	25646	73742
HTP inf. [kg DCB-Equiv.]	479649	19673	14731	23037	8864	352463	56629	1090	3161
MAETP inf. [kg DCB-Equiv.]	83498694	29944108	15339399	23956098	10261179	0	0	1031654	2966257
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	12168	254	325	517	126	9482	1418	12	34
TETP inf. [kg DCB-Equiv.]	1321	465	243	380	170	0	0	16	46
Ashton									
ADP elements [kg Sb-Equiv.]	1.86	1.08	0.23	0.35	0.17	0.00	0.00	0.01	0.03
ADP fossil [MJ]	27408798	11518381	4524304	7066072	3499536	0	0	206569	593936
AP [kg SO2-Equiv.]	188271	6908	2596	4066	1488	148246	24680	74	214
EP [kg Phosphate-Equiv.]	48161	2002	581	910	314	38171	6125	15	43
FAETP inf. [kg DCB-Equiv.]	4193	1569	746	1167	582	0	0	33	96
GWP 100 years [kg CO2-Equiv.]	3034478	-76461393	4229258	591917	1527552	69969071	3110489	17439	50144
HTP inf. [kg DCB-Equiv.]	484008	24103	14731	23037	10154	352463	56629	741	2149
MAETP inf. [kg DCB-Equiv.]	90310875	36543084	15339399	23956098	11753714	0	0	701525	2017054
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	12241	323	325	517	145	9482	1418	8	23
TETP inf. [kg DCB-Equiv.]	1431	570	243	380	195	0	0	11	32
Rural Cederberge									
ADP elements [kg Sb-Equiv.]	1.95	1.19	0.23	0.35	0.14	0.00	0.00	0.01	0.03
ADP fossil [MJ]	26417447	11016109	4524304	7066072	2916280	0	0	230871	663811
AP [kg SO2-Equiv.]	187208	6060	2596	4066	1240	148246	24680	82	239
EP [kg Phosphate-Equiv.]	47836	1722	581	910	261	38171	6125	17	48
FAETP inf. [kg DCB-Equiv.]	4086	1543	746	1167	485	0	0	37	107
GWP 100 years [kg CO2-Equiv.]	2438265	-76444891	4229258	591917	906887	69969071	3110489	19491	56044
HTP inf. [kg DCB-Equiv.]	481802	23250	14731	23037	8461	352463	56629	828	2402
MAETP inf. [kg DCB-Equiv.]	87105572	34976901	15339399	23956098	9794762	0	0	784057	2254355
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	12232	334	325	517	121	9482	1418	9	26
TETP inf. [kg DCB-Equiv.]	1385	551	243	380	163	0	0	12	35

Annexure 29: LCA results – LBS 29

Paarl	∑	Prim. production	Comminution	Forwarding	Harvesting	bio-char for sale	Combustion	Conversion	Transp.	Transp.
ADP elements [kg Sb-Equiv.]	2.05	0.98	0.30	0.47	0.16	0.00	0.00	0.00	0.04	0.11
ADP fossil [MJ]	32530355	10885596	5972722	9328216	3422136	0	0	0	753936	2167749
AP [kg SO2-Equiv.]	120871	6675	3427	5368	1455	0	70317	32582	269	780
EP [kg Phosphate-Equiv.]	30563	1943	767	1202	307	0	18047	8086	54	157
FAETP inf. [kg DCB-Equiv.]	5038	1471	985	1541	569	0	0	0	122	350
GWP 100 years [kg CO2-Equiv.]	-34228695	-103292643	5583219	781414	1649974	8929400	47766987	4106287	63650	183017
HTP inf. [kg DCB-Equiv.]	334485	22726	19447	30412	9929	0	166661	74759	2704	7845
MAETP inf. [kg DCB-Equiv.]	107819886	34528231	20250179	31625442	11493754	0	0	0	2560427	7361852
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	8282	298	429	683	141	0	4745	1871	29	85
TETP inf. [kg DCB-Equiv.]	1706	537	321	502	191	0	0	0	40	115
Worcester									**of bio-char**	**of bio-oil**
ADP elements [kg Sb-Equiv.]	2.11	1.08	0.30	0.47	0.19	0.00	0.00	0.00	0.02	0.06
ADP fossil [MJ]	33353181	12464924	5972722	9328216	4033231	0	0	0	401030	1153058
AP [kg SO2-Equiv.]	121754	7789	3427	5368	1715	0	70317	32582	143	415
EP [kg Phosphate-Equiv.]	30852	2276	767	1202	361	0	18047	8086	29	84
FAETP inf. [kg DCB-Equiv.]	5121	1673	985	1541	671	0	0	0	65	186
GWP 100 years [kg CO2-Equiv.]	-33016958	-102444185	5583219	781414	2128715	8929400	47766987	4106287	33856	97349
HTP inf. [kg DCB-Equiv.]	334564	25971	19447	30412	11702	0	166661	74759	1439	4173
MAETP inf. [kg DCB-Equiv.]	110230102	39530463	20250179	31625442	13546210	0	0	0	1361929	3915879
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	8290	335	429	683	167	0	4745	1871	15	45
TETP inf. [kg DCB-Equiv.]	1744	614	321	502	225	0	0	0	21	61
Ashton										
ADP elements [kg Sb-Equiv.]	2.46	1.42	0.30	0.47	0.22	0.00	0.00	0.00	0.01	0.04
ADP fossil [MJ]	36183495	15205894	5972722	9328216	4619883	0	0	0	272700	784080
AP [kg SO2-Equiv.]	123156	9120	3427	5368	1964	0	70317	32582	97	282
EP [kg Phosphate-Equiv.]	31235	2643	767	1202	414	0	18047	8086	20	57
FAETP inf. [kg DCB-Equiv.]	5536	2071	985	1541	768	0	0	0	44	127
GWP 100 years [kg CO2-Equiv.]	-31666756	-100939867	5583219	781414	2016585	8929400	47766987	4106287	23022	66198
HTP inf. [kg DCB-Equiv.]	340319	31820	19447	30412	13404	0	166661	74759	978	2838
MAETP inf. [kg DCB-Equiv.]	119223145	48242046	20250179	31625442	15516567	0	0	0	926112	2662798
ODP, steady state [kg R11-Equiv.]	0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	8387	426	429	683	191	0	4745	1871	11	31
TETP inf. [kg DCB-Equiv.]	1890	753	321	502	258	0	0	0	14	42
Rural Cederberge										
ADP elements [kg Sb-Equiv.]	2.58	1.57	0.30	0.47	0.18	0.00	0.00	0.00	0.02	0.04
ADP fossil [MJ]	34874771	14542824	5972722	9328216	3849903	0	0	0	304783	876324
AP [kg SO2-Equiv.]	121754	8000	3427	5368	1637	0	70317	32582	109	315
EP [kg Phosphate-Equiv.]	30806	2274	767	1202	345	0	18047	8086	22	64
FAETP inf. [kg DCB-Equiv.]	5394	2037	985	1541	640	0	0	0	49	142
GWP 100 years [kg CO2-Equiv.]	-32453840	-100918083	5583219	781414	1197219	8929400	47766987	4106287	25731	73986
HTP inf. [kg DCB-Equiv.]	337407	30693	19447	30412	11170	0	166661	74759	1093	3171
MAETP inf. [kg DCB-Equiv.]	114991691	46174463	20250179	31625442	12930473	0	0	0	1035066	2976068
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	8374	441	429	683	159	0	4745	1871	12	34
TETP inf. [kg DCB-Equiv.]	1828	728	321	502	215	0	0	0	16	46

Annexure 30: LCA results – LBS 30

Paarl	∑	Primary production	Forwarding	Harvesting	Combustion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.25	0.59	0.28	0.10	0.00	0.01	0.28
ADP fossil [MJ]	31169933	6569892	5629951	2065396	0	11411139	5493556
AP [kg SO2-Equiv.]	140147	4028	3240	878	115926	14115	1961
EP [kg Phosphate-Equiv.]	32711	1173	725	185	29608	625	395
FAETP inf. [kg DCB-Equiv.]	4680	888	930	343	0	1631	888
GWP 100 years [kg CO2-Equiv.]	904774	-62341235	471615	995825	60120377	1194405	463787
HTP inf. [kg DCB-Equiv.]	943632	13716	18355	5993	546597	339266	19706
MAETP inf. [kg DCB-Equiv.]	3389881728	20839167	19087217	6936939	0	3324361844	18656560
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	8179	180	412	85	6562	726	212
TETP inf. [kg DCB-Equiv.]	4911	324	303	115	0	3877	291
Worcester							
ADP elements [kg Sb-Equiv.]	1.20	0.65	0.28	0.12	0.00	0.01	0.14
ADP fossil [MJ]	29859613	7523079	5629951	2434216	0	11411139	2861227
AP [kg SO2-Equiv.]	140037	4701	3240	1035	115926	14115	1021
EP [kg Phosphate-Equiv.]	32756	1374	725	218	29608	625	206
FAETP inf. [kg DCB-Equiv.]	4438	1010	930	405	0	1631	462
GWP 100 years [kg CO2-Equiv.]	1483559	-61829157	471615	1284764	60120377	1194405	241556
HTP inf. [kg DCB-Equiv.]	937218	15675	18355	7063	546597	339266	10263
MAETP inf. [kg DCB-Equiv.]	3385199911	23858213	19087217	8175678	0	3324361844	9716958
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	8114	202	412	101	6562	726	111
TETP inf. [kg DCB-Equiv.]	4838	370	303	136	0	3877	152
Ashton							
ADP elements [kg Sb-Equiv.]	1.38	0.86	0.28	0.13	0.00	0.01	0.10
ADP fossil [MJ]	30952373	9177364	5629951	2788284	0	11411139	1945634
AP [kg SO2-Equiv.]	140664	5504	3240	1185	115926	14115	694
EP [kg Phosphate-Equiv.]	32943	1595	725	250	29608	625	140
FAETP inf. [kg DCB-Equiv.]	4589	1250	930	464	0	1631	314
GWP 100 years [kg CO2-Equiv.]	2246503	-60921241	471615	1217089	60120377	1194405	164258
HTP inf. [kg DCB-Equiv.]	938491	19204	18355	8090	546597	339266	6979
MAETP inf. [kg DCB-Equiv.]	3388537463	29116002	19087217	9364868	0	3324361844	6607532
ODP, steady state [kg R11-Equiv.]	0.05	0.03	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	8149	257	412	115	6562	726	75
TETP inf. [kg DCB-Equiv.]	4893	454	303	156	0	3877	103
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.45	0.95	0.28	0.11	0.00	0.01	0.10
ADP fossil [MJ]	30201918	8777175	5629951	2323570	0	11411139	2060084
AP [kg SO2-Equiv.]	139831	4828	3240	988	115926	14115	735
EP [kg Phosphate-Equiv.]	32687	1372	725	208	29608	625	148
FAETP inf. [kg DCB-Equiv.]	4509	1229	930	386	0	1631	333
GWP 100 years [kg CO2-Equiv.]	1774793	-60908093	471615	722570	60120377	1194405	173920
HTP inf. [kg DCB-Equiv.]	936873	18524	18355	6742	546597	339266	7390
MAETP inf. [kg DCB-Equiv.]	3386117461	27868133	19087217	7804057	0	3324361844	6996210
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.03	0.00
POCP [kg Ethene-Equiv.]	8143	266	412	96	6562	726	80
TETP inf. [kg DCB-Equiv.]	4858	439	303	130	0	3877	109

Annexure 31: LCA results – LBS 31

Paarl	∑	Primary production	Forwarding	Harvesting	Conversion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.08	0.51	0.24	0.08	0.00	0.01	0.24
ADP fossil [MJ]	26832495	5655662	4846517	1777986	0	9823227	4729103
AP [kg SO2-Equiv.]	96138	3468	2789	756	75287	12151	1688
EP [kg Phosphate-Equiv.]	21787	1010	624	159	19116	538	340
FAETP inf. [kg DCB-Equiv.]	4029	764	800	296	0	1404	764
GWP 100 years [kg CO2-Equiv.]	778870	-53666169	405987	857252	51754353	1028198	399249
HTP inf. [kg DCB-Equiv.]	518381	11808	15801	5159	176594	292056	16964
MAETP inf. [kg DCB-Equiv.]	2918164280	17939302	16431144	5971633	0	2861761786	16060415
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	5668	155	355	73	4277	625	183
TETP inf. [kg DCB-Equiv.]	4228	279	261	99	0	3338	251
Worcester							
ADP elements [kg Sb-Equiv.]	1.03	0.56	0.24	0.10	0.00	0.01	0.12
ADP fossil [MJ]	25704512	6476209	4846517	2095484	0	9823227	2463074
AP [kg SO2-Equiv.]	96042	4047	2789	891	75287	12151	879
EP [kg Phosphate-Equiv.]	21826	1183	624	188	19116	538	177
FAETP inf. [kg DCB-Equiv.]	3820	869	800	348	0	1404	398
GWP 100 years [kg CO2-Equiv.]	1277115	-53225349	405987	1105984	51754353	1028198	207942
HTP inf. [kg DCB-Equiv.]	512859	13493	15801	6080	176594	292056	8835
MAETP inf. [kg DCB-Equiv.]	2914133960	20538234	16431144	7037996	0	2861761786	8364800
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	5613	174	355	87	4277	625	95
TETP inf. [kg DCB-Equiv.]	4165	319	261	117	0	3338	131
Ashton							
ADP elements [kg Sb-Equiv.]	1.19	0.74	0.24	0.11	0.00	0.01	0.08
ADP fossil [MJ]	26645209	7900292	4846517	2400282	0	9823227	1674891
AP [kg SO2-Equiv.]	96582	4738	2789	1020	75287	12151	598
EP [kg Phosphate-Equiv.]	21987	1373	624	215	19116	538	120
FAETP inf. [kg DCB-Equiv.]	3950	1076	800	399	0	1404	271
GWP 100 years [kg CO2-Equiv.]	1933892	-52443774	405987	1047726	51754353	1028198	141401
HTP inf. [kg DCB-Equiv.]	513955	16532	15801	6964	176594	292056	6008
MAETP inf. [kg DCB-Equiv.]	2917007076	25064378	16431144	8061704	0	2861761786	5688064
ODP, steady state [kg R11-Equiv.]	0.05	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	5642	222	355	99	4277	625	65
TETP inf. [kg DCB-Equiv.]	4212	391	261	134	0	3338	89
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	1.25	0.81	0.24	0.10	0.00	0.01	0.09
ADP fossil [MJ]	25999184	7555791	4846517	2000235	0	9823227	1773414
AP [kg SO2-Equiv.]	95865	4156	2789	850	75287	12151	633
EP [kg Phosphate-Equiv.]	21766	1181	624	179	19116	538	127
FAETP inf. [kg DCB-Equiv.]	3882	1058	800	333	0	1404	287
GWP 100 years [kg CO2-Equiv.]	1527822	-52432455	405987	622021	51754353	1028198	149718
HTP inf. [kg DCB-Equiv.]	512562	15947	15801	5803	176594	292056	6361
MAETP inf. [kg DCB-Equiv.]	2914923828	23990155	16431144	6718087	0	2861761786	6022656
ODP, steady state [kg R11-Equiv.]	0.04	0.02	0.00	0.00	0.00	0.02	0.00
POCP [kg Ethene-Equiv.]	5637	229	355	83	4277	625	69
TETP inf. [kg DCB-Equiv.]	4182	378	261	112	0	3338	94

Annexure 32: LCA results – LBS 32

Paarl	∑	Primary production	Forwarding	Harvesting	Conversion	Comminution	Secondary transport
ADP elements [kg Sb-Equiv.]	1.78	0.84	0.40	0.14	0.00	0.01	0.39
ADP fossil [MJ]	44237105	9324146	7990159	2931258	0	16194958	7796585
AP [kg SO2-Equiv.]	237185	5717	4598	1246	202810	20032	2783
EP [kg Phosphate-Equiv.]	56346	1665	1029	263	51942	887	560
FAETP inf. [kg DCB-Equiv.]	6642	1260	1320	487	0	2315	1260
GWP 100 years [kg CO2-Equiv.]	1206508	-88476153	669327	1413299	85246691	1695127	658217
HTP inf. [kg DCB-Equiv.]	1043194	19466	26050	8505	479712	481494	27967
MAETP inf. [kg DCB-Equiv.]	4811000195	29575437	27089030	9845068	0	4718012829	26477831
ODP, steady state [kg R11-Equiv.]	0.07	0.03	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	15069	256	585	121	12775	1031	301
TETP inf. [kg DCB-Equiv.]	6970	460	430	164	0	5503	414
Worcester							
ADP elements [kg Sb-Equiv.]	1.70	0.92	0.40	0.16	0.00	0.01	0.20
ADP fossil [MJ]	42377467	10676932	7990159	3454697	0	16194958	4060721
AP [kg SO2-Equiv.]	237029	6671	4598	1469	202810	20032	1449
EP [kg Phosphate-Equiv.]	56410	1950	1029	310	51942	887	292
FAETP inf. [kg DCB-Equiv.]	6298	1433	1320	575	0	2315	656
GWP 100 years [kg CO2-Equiv.]	2027935	-87749400	669327	1823368	85246691	1695127	342822
HTP inf. [kg DCB-Equiv.]	1034091	22246	26050	10023	479712	481494	14566
MAETP inf. [kg DCB-Equiv.]	4804355651	33860139	27089030	11603116	0	4718012829	13790537
ODP, steady state [kg R11-Equiv.]	0.07	0.03	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	14978	287	585	143	12775	1031	157
TETP inf. [kg DCB-Equiv.]	6867	526	430	193	0	5503	215
Ashton							
ADP elements [kg Sb-Equiv.]	1.96	1.22	0.40	0.19	0.00	0.01	0.14
ADP fossil [MJ]	43928338	13024732	7990159	3957199	0	16194958	2761290
AP [kg SO2-Equiv.]	237919	7812	4598	1682	202810	20032	986
EP [kg Phosphate-Equiv.]	56676	2264	1029	355	51942	887	198
FAETP inf. [kg DCB-Equiv.]	6512	1774	1320	658	0	2315	446
GWP 100 years [kg CO2-Equiv.]	3110722	-86460864	669327	1727322	85246691	1695127	233119
HTP inf. [kg DCB-Equiv.]	1035898	27255	26050	11481	479712	481494	9905
MAETP inf. [kg DCB-Equiv.]	4809092383	41322117	27089030	13290842	0	4718012829	9377565
ODP, steady state [kg R11-Equiv.]	0.08	0.04	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	15026	365	585	164	12775	1031	107
TETP inf. [kg DCB-Equiv.]	6945	645	430	221	0	5503	146
Rural Cederberge							
ADP elements [kg Sb-Equiv.]	2.06	1.34	0.40	0.16	0.00	0.01	0.15
ADP fossil [MJ]	42863275	12456774	7990159	3297665	0	16194958	2923719
AP [kg SO2-Equiv.]	236737	6852	4598	1402	202810	20032	1044
EP [kg Phosphate-Equiv.]	56312	1948	1029	296	51942	887	210
FAETP inf. [kg DCB-Equiv.]	6400	1745	1320	548	0	2315	473
GWP 100 years [kg CO2-Equiv.]	2441260	-86442205	669327	1025488	85246691	1695127	246831
HTP inf. [kg DCB-Equiv.]	1033601	26290	26050	9568	479712	481494	10488
MAETP inf. [kg DCB-Equiv.]	4805657858	39551112	27089030	11075702	0	4718012829	9929187
ODP, steady state [kg R11-Equiv.]	0.07	0.03	0.00	0.00	0.00	0.04	0.00
POCP [kg Ethene-Equiv.]	15018	378	585	136	12775	1031	113
TETP inf. [kg DCB-Equiv.]	6895	623	430	184	0	5503	155

Annexure 33: LCA results – LBS 33

Paarl	∑	Primary production	Harvesting	Forwarding	Combustion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.22	0.61	0.17	0.09	0.00	0.35
ADP fossil [MJ]	18957852	6777362	3401391	1857218	0	6921881
AP [kg SO2-Equiv.]	124578	4156	960	1066	115926	2471
EP [kg Phosphate-Equiv.]	31732	1210	179	238	29608	497
FAETP inf. [kg DCB-Equiv.]	2945	916	604	306	0	1119
GWP 100 years [kg CO2-Equiv.]	-23	-64309906	3449529	155605	60120377	584371
HTP inf. [kg DCB-Equiv.]	600370	14149	8747	6047	546597	24829
MAETP inf. [kg DCB-Equiv.]	62833539	21497246	11532234	6296793	0	23507266
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7659	186	510	133	6562	268
TETP inf. [kg DCB-Equiv.]	989	335	188	100	0	367
Worcester						
ADP elements [kg Sb-Equiv.]	1.12	0.67	0.17	0.09	0.00	0.18
ADP fossil [MJ]	16624406	7760650	3401391	1857218	0	3605146
AP [kg SO2-Equiv.]	124087	4849	960	1066	115926	1287
EP [kg Phosphate-Equiv.]	31701	1417	179	238	29608	259
FAETP inf. [kg DCB-Equiv.]	2535	1042	604	306	0	583
GWP 100 years [kg CO2-Equiv.]	248215	-63781657	3449529	155605	60120377	304360
HTP inf. [kg DCB-Equiv.]	590493	16170	8747	6047	546597	12932
MAETP inf. [kg DCB-Equiv.]	54684025	24611630	11532234	6296793	0	12243368
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7554	209	510	133	6562	139
TETP inf. [kg DCB-Equiv.]	861	382	188	100	0	191
Ashton						
ADP elements [kg Sb-Equiv.]	1.27	0.89	0.17	0.09	0.00	0.12
ADP fossil [MJ]	17177284	9467176	3401391	1857218	0	2451499
AP [kg SO2-Equiv.]	124504	5678	960	1066	115926	875
EP [kg Phosphate-Equiv.]	31847	1645	179	238	29608	176
FAETP inf. [kg DCB-Equiv.]	2596	1289	604	306	0	396
GWP 100 years [kg CO2-Equiv.]	1087406	-62845070	3449529	155605	60120377	206965
HTP inf. [kg DCB-Equiv.]	589996	19811	8747	6047	546597	8794
MAETP inf. [kg DCB-Equiv.]	56189972	30035454	11532234	6296793	0	8325490
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7566	265	510	133	6562	95
TETP inf. [kg DCB-Equiv.]	886	469	188	100	0	130
Rural Cederberge						
ADP elements [kg Sb-Equiv.]	1.37	0.98	0.17	0.09	0.00	0.13
ADP fossil [MJ]	16908663	9054349	3401391	1857218	0	2595705
AP [kg SO2-Equiv.]	123859	4981	960	1066	115926	926
EP [kg Phosphate-Equiv.]	31627	1416	179	238	29608	186
FAETP inf. [kg DCB-Equiv.]	2598	1268	604	306	0	420
GWP 100 years [kg CO2-Equiv.]	1113144	-62831507	3449529	155605	60120377	219139
HTP inf. [kg DCB-Equiv.]	589811	19109	8747	6047	546597	9311
MAETP inf. [kg DCB-Equiv.]	55392431	28748179	11532234	6296793	0	8815225
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	7581	275	510	133	6562	100
TETP inf. [kg DCB-Equiv.]	878	453	188	100	0	138

Annexure 34 LCA results – LBS 34

Paarl	∑	Primary production	Harvesting	Forwarding	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.05	0.52	0.15	0.08	0.00	0.30
ADP fossil [MJ]	16319781	5834261	2928072	1598778	0	5958670
AP [kg SO2-Equiv.]	82735	3577	827	917	75287	2127
EP [kg Phosphate-Equiv.]	20945	1042	154	205	19116	428
FAETP inf. [kg DCB-Equiv.]	2535	788	520	264	0	963
GWP 100 years [kg CO2-Equiv.]	-20	-55360890	2969511	133952	51754353	503054
HTP inf. [kg DCB-Equiv.]	222884	12180	7530	5206	176594	21374
MAETP inf. [kg DCB-Equiv.]	54089966	18505806	9927471	5420566	0	20236123
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5221	160	439	115	4277	230
TETP inf. [kg DCB-Equiv.]	852	288	162	86	0	316
Worcester						
ADP elements [kg Sb-Equiv.]	0.96	0.58	0.15	0.08	0.00	0.16
ADP fossil [MJ]	14311044	6680721	2928072	1598778	0	3103474
AP [kg SO2-Equiv.]	82313	4174	827	917	75287	1108
EP [kg Phosphate-Equiv.]	20918	1220	154	205	19116	223
FAETP inf. [kg DCB-Equiv.]	2182	897	520	264	0	502
GWP 100 years [kg CO2-Equiv.]	213674	-54906149	2969511	133952	51754353	262007
HTP inf. [kg DCB-Equiv.]	214382	13919	7530	5206	176594	11132
MAETP inf. [kg DCB-Equiv.]	47074495	21186810	9927471	5420566	0	10539647
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5130	180	439	115	4277	120
TETP inf. [kg DCB-Equiv.]	741	329	162	86	0	165
Ashton						
ADP elements [kg Sb-Equiv.]	1.10	0.76	0.15	0.08	0.00	0.11
ADP fossil [MJ]	14786987	8149775	2928072	1598778	0	2110362
AP [kg SO2-Equiv.]	82672	4888	827	917	75287	753
EP [kg Phosphate-Equiv.]	21043	1416	154	205	19116	152
FAETP inf. [kg DCB-Equiv.]	2235	1110	520	264	0	341
GWP 100 years [kg CO2-Equiv.]	936089	-54099893	2969511	133952	51754353	178165
HTP inf. [kg DCB-Equiv.]	213954	17054	7530	5206	176594	7570
MAETP inf. [kg DCB-Equiv.]	48370882	25855884	9927471	5420566	0	7166960
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5141	228	439	115	4277	82
TETP inf. [kg DCB-Equiv.]	763	403	162	86	0	112
Rural Cederberge						
ADP elements [kg Sb-Equiv.]	1.18	0.84	0.15	0.08	0.00	0.11
ADP fossil [MJ]	14555746	7794395	2928072	1598778	0	2234501
AP [kg SO2-Equiv.]	82116	4288	827	917	75287	798
EP [kg Phosphate-Equiv.]	20854	1219	154	205	19116	161
FAETP inf. [kg DCB-Equiv.]	2237	1092	520	264	0	361
GWP 100 years [kg CO2-Equiv.]	958245	-54088217	2969511	133952	51754353	188645
HTP inf. [kg DCB-Equiv.]	213795	16450	7530	5206	176594	8015
MAETP inf. [kg DCB-Equiv.]	47684322	24747739	9927471	5420566	0	7588546
ODP, steady state [kg R11-Equiv.]	0.02	0.02	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	5154	236	439	115	4277	86
TETP inf. [kg DCB-Equiv.]	756	390	162	86	0	119

Annexure 35: LCA results – LBS 35

Paarl	∑	Primary production	Harvesting	Forwarding	Conversion	Secondary transport
ADP elements [kg Sb-Equiv.]	1.73	0.86	0.24	0.13	0.00	0.50
ADP fossil [MJ]	26905431	9618592	4827335	2635808	0	9823697
AP [kg SO2-Equiv.]	215089	5898	1363	1512	202810	3506
EP [kg Phosphate-Equiv.]	54958	1717	254	338	51942	706
FAETP inf. [kg DCB-Equiv.]	4180	1300	858	435	0	1588
GWP 100 years [kg CO2-Equiv.]	-77600	-91270137	4895653	220839	85246691	829354
HTP inf. [kg DCB-Equiv.]	556028	20081	12414	8582	479712	35238
MAETP inf. [kg DCB-Equiv.]	89174842	30509399	16366819	8936557	0	33362067
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14332	264	724	189	12775	380
TETP inf. [kg DCB-Equiv.]	1404	475	267	142	0	521
Worcester						
ADP elements [kg Sb-Equiv.]	1.58	0.95	0.24	0.13	0.00	0.26
ADP fossil [MJ]	23593749	11014098	4827335	2635808	0	5116509
AP [kg SO2-Equiv.]	214393	6882	1363	1512	202810	1826
EP [kg Phosphate-Equiv.]	54914	2011	254	338	51942	368
FAETP inf. [kg DCB-Equiv.]	3598	1478	858	435	0	827
GWP 100 years [kg CO2-Equiv.]	274705	-90520434	4895653	220839	85246691	431955
HTP inf. [kg DCB-Equiv.]	542010	22948	12414	8582	479712	18353
MAETP inf. [kg DCB-Equiv.]	77608860	34929407	16366819	8936557	0	17376077
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14182	296	724	189	12775	198
TETP inf. [kg DCB-Equiv.]	1222	542	267	142	0	271
Ashton						
ADP elements [kg Sb-Equiv.]	1.81	1.26	0.24	0.13	0.00	0.18
ADP fossil [MJ]	24378408	13436039	4827335	2635808	0	3479226
AP [kg SO2-Equiv.]	214985	8058	1363	1512	202810	1242
EP [kg Phosphate-Equiv.]	55120	2335	254	338	51942	250
FAETP inf. [kg DCB-Equiv.]	3684	1830	858	435	0	562
GWP 100 years [kg CO2-Equiv.]	1465705	-89191207	4895653	220839	85246691	293729
HTP inf. [kg DCB-Equiv.]	541304	28116	12414	8582	479712	12480
MAETP inf. [kg DCB-Equiv.]	79746134	42627026	16366819	8936557	0	11815732
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14200	377	724	189	12775	134
TETP inf. [kg DCB-Equiv.]	1258	665	267	142	0	185
Rural Cederberge						
ADP elements [kg Sb-Equiv.]	1.95	1.39	0.24	0.13	0.00	0.19
ADP fossil [MJ]	23997174	12850146	4827335	2635808	0	3683886
AP [kg SO2-Equiv.]	214068	7069	1363	1512	202810	1315
EP [kg Phosphate-Equiv.]	54809	2009	254	338	51942	265
FAETP inf. [kg DCB-Equiv.]	3688	1800	858	435	0	595
GWP 100 years [kg CO2-Equiv.]	1502232	-89171958	4895653	220839	85246691	311008
HTP inf. [kg DCB-Equiv.]	541043	27120	12414	8582	479712	13214
MAETP inf. [kg DCB-Equiv.]	78614246	40800094	16366819	8936557	0	12510775
ODP, steady state [kg R11-Equiv.]	0.04	0.03	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	14221	390	724	189	12775	142
TETP inf. [kg DCB-Equiv.]	1247	643	267	142	0	195

Annexure 36: LCA results – LBS 36

Paarl	∑	Primary production	Harvesting	Forwarding	Conversion	Upgrading	transport of bio-char	transport of bio-oil
ADP elements [kg Sb-Equiv.]	1.17	0.74	0.21	0.11	0.00	0.00	0.03	0.08
ADP fossil [MJ]	16903993	8245779	4138353	2259612	0	0	583253	1676996
AP [kg SO2-Equiv.]	181258	5056	1169	1296	148246	24680	208	603
EP [kg Phosphate-Equiv.]	46440	1472	218	290	38171	6125	42	122
FAETP inf. [kg DCB-Equiv.]	2588	1114	735	373	0	0	94	271
GWP 100 years [kg CO2-Equiv.]	-586982	-78243608	4196921	189319	69969071	3110489	49240	141584
HTP inf. [kg DCB-Equiv.]	452469	17215	10643	7357	352463	56629	2092	6069
MAETP inf. [kg DCB-Equiv.]	55522885	26154945	14030865	7661087	0	0	1980776	5695213
ODP, steady state [kg R11-Equiv.]	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	11997	226	621	162	9482	1418	23	66
TETP inf. [kg DCB-Equiv.]	877	407	228	121	0	0	31	89
Worcester								
ADP elements [kg Sb-Equiv.]	1.19	0.82	0.21	0.11	0.00	0.00	0.02	0.04
ADP fossil [MJ]	17017290	9442111	4138353	2259612	0	0	303778	873435
AP [kg SO2-Equiv.]	181714	5900	1169	1296	148246	24680	108	314
EP [kg Phosphate-Equiv.]	46614	1724	218	290	38171	6125	22	63
FAETP inf. [kg DCB-Equiv.]	2565	1267	735	373	0	0	49	141
GWP 100 years [kg CO2-Equiv.]	-35717	-77600906	4196921	189319	69969071	3110489	25646	73742
HTP inf. [kg DCB-Equiv.]	451016	19673	10643	7357	352463	56629	1090	3161
MAETP inf. [kg DCB-Equiv.]	55633970	29944108	14030865	7661087	0	0	1031654	2966257
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	11983	254	621	162	9482	1418	12	34
TETP inf. [kg DCB-Equiv.]	877	465	228	121	0	0	16	46
Ashton								
ADP elements [kg Sb-Equiv.]	1.44	1.08	0.21	0.11	0.00	0.00	0.01	0.03
ADP fossil [MJ]	18716851	11518381	4138353	2259612	0	0	206569	593936
AP [kg SO2-Equiv.]	182587	6908	1169	1296	148246	24680	74	214
EP [kg Phosphate-Equiv.]	46864	2002	218	290	38171	6125	15	43
FAETP inf. [kg DCB-Equiv.]	2806	1569	735	373	0	0	33	96
GWP 100 years [kg CO2-Equiv.]	1071992	-76461393	4196921	189319	69969071	3110489	17439	50144
HTP inf. [kg DCB-Equiv.]	454086	24103	10643	7357	352463	56629	741	2149
MAETP inf. [kg DCB-Equiv.]	60953615	36543084	14030865	7661087	0	0	701525	2017054
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	12037	323	621	162	9482	1418	8	23
TETP inf. [kg DCB-Equiv.]	963	570	228	121	0	0	11	32
Rural Cederberge								
ADP elements [kg Sb-Equiv.]	1.55	1.19	0.21	0.11	0.00	0.00	0.01	0.03
ADP fossil [MJ]	18261668	11016109	4138353	2259612	0	0	218720	628873
AP [kg SO2-Equiv.]	181755	6060	1169	1296	148246	24680	78	226
EP [kg Phosphate-Equiv.]	46588	1722	218	290	38171	6125	16	46
FAETP inf. [kg DCB-Equiv.]	2788	1543	735	373	0	0	35	102
GWP 100 years [kg CO2-Equiv.]	1092469	-76444891	4196921	189319	69969071	3110489	18465	53094
HTP inf. [kg DCB-Equiv.]	453402	23250	10643	7357	352463	56629	785	2276
MAETP inf. [kg DCB-Equiv.]	59547349	34976901	14030865	7661087	0	0	742791	2135705
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	12050	334	621	162	9482	1418	8	25
TETP inf. [kg DCB-Equiv.]	946	551	228	121	0	0	12	33

Annexure 37: LCA results – LBS 37

Paarl	∑	Primary production	Harvesting	Forwarding	bio-char for sale	Conversion	Upgrading	Transp. of bio-char	Transp. of bio-oil
ADP elements [kg Sb-Equiv.]	1.55	0.98	0.27	0.15	0.00	0.00	0.00	0.04	0.11
ADP fossil [MJ]	22315665	10885596	5463213	2983008	0	0	0	769977	2213872
AP [kg SO2-Equiv.]	113899	6675	1543	1711	0	70317	32582	275	796
EP [kg Phosphate-Equiv.]	28963	1943	288	383	0	18047	8086	55	161
FAETP inf. [kg DCB-Equiv.]	3416	1471	971	492	0	0	0	124	358
GWP 100 years [kg CO2-Equiv.]	-36447596	-103292643	5540530	249928	8929400	47766987	4106287	65004	186911
HTP inf. [kg DCB-Equiv.]	298683	22726	14050	9713	0	166661	74759	2762	8012
MAETP inf. [kg DCB-Equiv.]	73298072	34528231	18522729	10113720	0	0	0	2614904	7518487
ODP, steady state [kg R11-Equiv.]	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	8065	298	819	214	0	4745	1871	30	87
TETP inf. [kg DCB-Equiv.]	1158	537	302	160	0	0	0	41	117
Worcester									
ADP elements [kg Sb-Equiv.]	1.58	1.08	0.27	0.15	0.00	0.00	0.00	0.02	0.06
ADP fossil [MJ]	22465232	12464924	5463213	2983008	0	0	0	401030	1153058
AP [kg SO2-Equiv.]	114500	7789	1543	1711	0	70317	32582	143	415
EP [kg Phosphate-Equiv.]	29193	2276	288	383	0	18047	8086	29	84
FAETP inf. [kg DCB-Equiv.]	3387	1673	971	492	0	0	0	65	186
GWP 100 years [kg CO2-Equiv.]	-35719847	-102444185	5540530	249928	8929400	47766987	4106287	33856	97349
HTP inf. [kg DCB-Equiv.]	296765	25971	14050	9713	0	166661	74759	1439	4173
MAETP inf. [kg DCB-Equiv.]	73444720	39530463	18522729	10113720	0	0	0	1361929	3915879
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	8046	335	819	214	0	4745	1871	15	45
TETP inf. [kg DCB-Equiv.]	1158	614	302	160	0	0	0	21	61
Ashton									
ADP elements [kg Sb-Equiv.]	1.90	1.42	0.27	0.15	0.00	0.00	0.00	0.01	0.04
ADP fossil [MJ]	24708894	15205894	5463213	2983008	0	0	0	272700	784080
AP [kg SO2-Equiv.]	115652	9120	1543	1711	0	70317	32582	97	282
EP [kg Phosphate-Equiv.]	29523	2643	288	383	0	18047	8086	20	57
FAETP inf. [kg DCB-Equiv.]	3704	2071	971	492	0	0	0	44	127
GWP 100 years [kg CO2-Equiv.]	-34257515	-100939867	5540530	249928	8929400	47766987	4106287	23022	66198
HTP inf. [kg DCB-Equiv.]	300818	31820	14050	9713	0	166661	74759	978	2838
MAETP inf. [kg DCB-Equiv.]	80467405	48242046	18522729	10113720	0	0	0	926112	2662798
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	8118	426	819	214	0	4745	1871	11	31
TETP inf. [kg DCB-Equiv.]	1271	753	302	160	0	0	0	14	42
Rural Cederberge									
ADP elements [kg Sb-Equiv.]	2.05	1.57	0.27	0.15	0.00	0.00	0.00	0.01	0.04
ADP fossil [MJ]	24107987	14542824	5463213	2983008	0	0	0	288741	830202
AP [kg SO2-Equiv.]	114554	8000	1543	1711	0	70317	32582	103	299
EP [kg Phosphate-Equiv.]	29158	2274	288	383	0	18047	8086	21	60
FAETP inf. [kg DCB-Equiv.]	3680	2037	971	492	0	0	0	47	134
GWP 100 years [kg CO2-Equiv.]	-34230482	-100918083	5540530	249928	8929400	47766987	4106287	24377	70092
HTP inf. [kg DCB-Equiv.]	299915	30693	14050	9713	0	166661	74759	1036	3005
MAETP inf. [kg DCB-Equiv.]	78610934	46174463	18522729	10113720	0	0	0	980589	2819433
ODP, steady state [kg R11-Equiv.]	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POCP [kg Ethene-Equiv.]	8135	441	819	214	0	4745	1871	11	32
TETP inf. [kg DCB-Equiv.]	1249	728	302	160	0	0	0	15	44

Annexure 38: LCA results – current power grid mix of South African

Life-Cycle Impact Assessment categories based on CML 2001 –Nov. 2009	**Unit**	**South African Power grid mix[1]**
ADP elements	kg Sb-Equiv.	0.26
ADP fossil	GJ	429458
AP	t SO_2-Equiv.	531
EP	t Phosphate-Equiv.	24
FAETP inf.	t DCB-Equiv.	61
GWP 100 years	t CO_2-Equiv.	44951
HTP inf.	t DCB-Equiv.	12768
MAETP inf.	t DCB-Equiv.	125112384
ODP, steady state	kg R11-Equiv.	0.949984761
POCP	t Ethene-Equiv.	27
TETP inf.	t DCB-Equiv.	146

Note:

1 Based on the functional unit of 39 600 MWh_{el}/a

Annexure 39: Abiotic Depletion Potential per LBS and BPA

LBS	Abiotic Depletion (ADP fossil) [GJ]			
	Paarl	Worcester	Ashton	R. Cederberge
1	24 341	23 741	25 507	23 950
2	20 567	20 341	21 861	20 714
3	34 386	33 694	36 200	34 150
4	25 277	26 650	29 514	27 578
5	33 619	35 307	39 460	36 407
6	31 677	30 964	32 630	31 127
7	26 875	26 556	27 991	26 894
8	44 794	43 944	46 309	44 338
9	38 511	40 160	45 193	40 567
10	32 959	34 475	38 904	34 729
11	54 656	56 997	64 139	57 573
12	42 297	46 449	52 750	47 390
13	56 274	61 443	69 948	62 562
14	46 332	47 793	52 660	48 158
15	39 687	41 044	45 332	41 260
16	65 755	67 829	74 736	68 348
17	20 891	19 675	20 849	20 069
18	17 597	16 840	17 851	17 373
19	29 489	27 923	29 590	28 642
20	21 080	21 703	23 847	22 856
21	27 829	28 651	31 482	30 173
22	28 332	27 022	28 115	27 364
23	24 390	23 262	24 202	23 556
24	40 210	38 350	39 901	38 836
25	23 818	22 602	23 777	22 997
26	20 117	19 360	20 371	19 893
27	33 644	32 077	33 744	32 796
28	24 642	25 265	27 409	26 417
29	32 530	33 353	36 183	34 875
30	31 170	29 860	30 952	30 202
31	26 832	25 705	26 645	25 999
32	44 237	42 377	43 928	42 863
33	18 958	16 624	17 177	16 909
34	16 320	14 311	14 787	14 556
35	26 905	23 594	24 378	23 997
36	16 904	17 017	18 717	18 262
37	22 316	22 465	24 709	24 108
Minimum	65 755	67 829	74 736	68 348
Maximum	16 320	14 311	14 787	14 556
Average	31 519	31 498	34 101	32 121

Annexure 40: Acidification Potential per LBS and BPA

LBS	Acidification Potential (AP) [t SO_2-Equiv.]			
	Paarl	Worcester	Ashton	R. Cederberge
1	126	126	126	125
2	84	84	84	84
3	217	217	217	216
4	183	184	185	184
5	117	117	119	117
6	138	137	138	137
7	94	94	94	94
8	234	233	234	233
9	129	130	131	130
10	87	87	88	87
11	222	222	224	222
12	188	189	190	189
13	122	124	126	124
14	142	142	143	142
15	97	98	99	97
16	239	240	241	239
17	126	126	127	126
18	84	84	85	84
19	217	217	218	217
20	184	184	186	184
21	117	118	120	118
22	138	138	138	138
23	94	94	95	94
24	234	234	235	234
25	128	128	129	128
26	86	86	86	86
27	220	220	221	220
28	187	187	188	187
29	121	122	123	122
30	140	140	141	140
31	96	96	97	96
32	237	237	238	237
33	125	124	125	124
34	83	82	83	82
35	215	214	215	214
36	181	182	183	182
37	114	114	116	115
Minimum	239	240	241	239
Maximum	83	82	83	82
Average	150	150	151	150

Annexure 41: Eutrophication Potential per LBS and BPA

LBS	Eutrophication Potential (EP) [t Phosphate-Equiv.]			
	Paarl	Worcester	Ashton	R. Cederberge
1	32	32	32	32
2	21	21	21	21
3	55	55	56	55
4	47	47	47	47
5	29	30	30	30
6	32	32	32	32
7	21	21	21	21
8	55	55	56	55
9	33	33	33	33
10	22	22	22	22
11	56	56	57	56
12	48	48	48	48
13	31	31	32	31
14	33	33	33	33
15	22	22	22	22
16	57	57	57	57
17	32	32	32	32
18	21	21	21	21
19	55	56	56	55
20	47	47	48	47
21	30	30	30	30
22	32	32	32	32
23	21	21	22	21
24	56	56	56	56
25	33	33	33	33
26	22	22	22	22
27	56	56	57	56
28	48	48	48	48
29	31	31	31	31
30	33	33	33	33
31	22	22	22	22
32	56	56	57	56
33	32	32	32	32
34	21	21	21	21
35	55	55	55	55
36	46	47	47	47
37	29	29	30	29
Minimum	57	57	57	57
Maximum	21	21	21	21
Average	37	37	37	37

Annexure 42: Global Warming Potential per LBS and BPA

LBS	Global Warming Potential (GWP 100 years) [t CO_2-Equiv.]			
	Paarl	Worcester	Ashton	R. Cederberge
1	133	471	1 358	1 346
2	82	397	1 161	1 167
3	97	591	1 850	1 847
4	-271	318	1 458	1 440
5	-36 010	-35 243	-33 707	-33 772
6	-183	134	990	979
7	-191	107	844	851
8	-351	112	1 327	1 326
9	34	642	2 039	1 928
10	13	545	1 755	1 643
11	-30	834	2 816	2 658
12	-411	511	2 225	2 113
13	-36 178	-34 988	-32 709	-32 884
14	-202	376	1 729	1 620
15	-191	315	1 489	1 378
16	-364	456	2 377	2 222
17	1 006	1 615	2 406	1 918
18	833	1 382	2 063	1 660
19	1 337	2 214	3 336	2 659
20	791	1 709	2 732	2 136
21	-34 628	-33 417	-32 066	-32 854
22	664	1 242	2 005	1 534
23	571	1 069	1 726	1 320
24	864	1 686	2 768	2 099
25	1 255	1 863	2 654	2 167
26	1 048	1 596	2 277	1 874
27	1 690	2 567	3 690	3 012
28	1 094	2 012	3 034	2 438
29	-34 229	-33 017	-31 667	-32 454
30	905	1 484	2 247	1 775
31	779	1 277	1 934	1 528
32	1 207	2 028	3 111	2 441
33	0	248	1 087	1 113
34	0	214	936	958
35	-78	275	1 466	1 502
36	-587	-36	1 072	1 092
37	-36 448	-35 720	-34 258	-34 230
Minimum	1 690	2 567	3 690	3 012
Maximum	-36 448	-35 720	-34 258	-34 230
Average	-4 485	-3 841	-2 715	-2 985

Annexure 43: Avoided net CO_2-equivalent emissions per LBS and BPA

LBS	Avoided CO_2-eqivalent emissions in tonnes/year			
	Paarl	Worcester	Ashton	R. Cederberge
1	39 701	39 815	39 760	39 809
2	39 935	40 012	39 964	39 991
3	39 095	39 245	39 167	39 224
4	39 714	39 332	39 570	39 633
5	39 228	39 208	39 018	39 139
6	38 916	39 037	38 987	39 034
7	39 260	39 342	39 299	39 324
8	37 981	38 141	38 070	38 124
9	39 235	39 286	39 092	39 245
10	39 519	39 556	39 381	39 528
11	38 421	38 495	38 219	38 436
12	39 164	39 062	38 812	38 978
13	38 487	38 376	38 032	38 274
14	38 392	38 452	38 264	38 414
15	38 794	38 838	38 669	38 813
16	37 225	37 311	37 045	37 257
17	38 814	38 656	38 694	39 222
18	39 172	39 014	39 047	39 486
19	37 837	37 600	37 655	38 391
20	38 636	38 282	38 274	38 919
21	37 823	37 356	37 345	38 197
22	38 057	37 913	37 954	38 465
23	38 491	38 367	38 402	38 842
24	36 750	36 546	36 604	37 329
25	38 580	38 421	38 459	38 987
26	38 970	38 811	38 844	39 284
27	37 504	37 266	37 321	38 058
28	38 350	37 995	37 988	38 633
29	37 446	36 978	36 967	37 819
30	37 829	37 685	37 726	38 237
31	38 294	38 171	38 206	38 646
32	36 426	36 223	36 281	37 006
33	39 817	40 011	39 998	40 015
34	40 006	40 173	40 161	40 176
35	39 248	39 523	39 505	39 529
36	39 995	40 005	39 910	39 941
37	39 618	39 631	39 506	39 546

Annexure 44: Photochemical Ozone Creation Potential per LBS and BPA

LBS	Photochem. Ozone Creation Potential (POCP) [t Ethene-Equivalent]			
	Paarl	Worcester	Ashton	R. Cederberge
1	9.1	9.4	9.7	9.3
2	6.5	6.7	7.0	6.6
3	16.4	16.8	17.2	16.7
4	13.9	14.2	14.6	14.2
5	10.5	11.0	11.6	10.9
6	9.5	9.8	10.1	9.7
7	6.8	7.0	7.3	7.0
8	17.0	17.3	17.7	17.2
9	12.6	13.5	14.4	13.3
10	9.5	10.2	11.0	10.0
11	21.4	22.6	23.9	22.3
12	18.1	19.2	20.4	19.0
13	16.2	17.6	19.1	17.3
14	13.0	13.8	14.7	13.6
15	9.8	10.5	11.3	10.3
16	21.9	23.1	24.4	22.8
17	7.5	7.4	7.5	7.5
18	5.1	5.0	5.0	5.1
19	14.1	14.0	14.1	14.1
20	11.9	11.9	11.9	11.9
21	7.9	7.9	8.0	8.0
22	7.9	7.9	7.9	7.9
23	5.5	5.4	5.4	5.4
24	14.7	14.6	14.7	14.7
25	7.7	7.7	7.7	7.7
26	5.3	5.2	5.3	5.3
27	14.4	14.4	14.4	14.4
28	12.2	12.2	12.2	12.2
29	8.3	8.3	8.4	8.4
30	8.2	8.1	8.1	8.1
31	5.7	5.6	5.6	5.6
32	15.1	15.0	15.0	15.0
33	7.7	7.6	7.6	7.6
34	5.2	5.1	5.1	5.2
35	14.3	14.2	14.2	14.2
36	12.0	12.0	12.0	12.1
37	8.1	8.0	8.1	8.1
Minimum	21.9	23.1	24.4	22.8
Maximum	5.1	5.0	5.0	5.1
Average	11.1	11.4	11.7	11.3

Annexure 45: IRR per LBS and BPA – including land value

LBS	Internal Rate of Return (IRR) on capital investment (%)			
	Paarl	Worcester	Ashton	R. Cederberge
1	9.86%	13.15%	9.10%	7.61%
2	10.33%	14.26%	9.37%	7.70%
3	-[a]	1.04%	-0.84%	-0.55%
4	2.58%	4.00%	2.38%	2.28%
5	3.98%	5.71%	3.70%	3.38%
6	9.96%	13.24%	9.30%	7.71%
7	10.46%	14.19%	9.52%	7.83%
8	-0.34%	1.81%	-0.25%	0.06%
9	6.80%	10.06%	6.24%	5.32%
10	6.80%	10.57%	6.17%	5.17%
11	-[a]	-2.00%	-4.31%	-2.83%
12	0.62%	2.12%	0.25%	0.52%
13	1.76%	3.54%	1.36%	1.42%
14	7.35%	10.62%	6.85%	5.73%
15	7.41%	11.07%	6.77%	5.55%
16	-	-0.38%	-2.84%	-1.78%
17	9.66%	12.85%	8.89%	7.49%
18	10.09%	13.96%	9.11%	7.55%
19	-[a]	0.57%	-1.26%	-0.87%
20	2.40%	3.75%	2.15%	2.10%
21	3.79%	5.45%	3.48%	3.23%
22	9.77%	12.94%	9.09%	7.59%
23	10.21%	13.88%	9.26%	7.68%
24	-0.71%	1.36%	-0.64%	-0.24%
25	10.49%	14.07%	9.77%	8.04%
26	10.96%	15.15%	9.95%	8.12%
27	0.36%	2.85%	0.74%	0.62%
28	3.25%	4.86%	3.13%	2.84%
29	4.82%	6.82%	4.70%	4.12%
30	10.60%	14.04%	9.97%	8.14%
31	11.09%	15.07%	10.11%	8.25%
32	0.67%	3.15%	1.02%	0.97%
33	10.64%	14.07%	9.82%	8.14%
34	11.18%	15.26%	10.13%	8.25%
35	0.86%	3.22%	1.16%	1.01%
36	3.48%	5.05%	3.33%	3.05%
37	4.89%	6.77%	4.65%	4.13%
Minimum	-[a]	-2.00%	-4.31%	-2.83%
Maximum	11.18%	15.26%	10.13%	8.25%
Average	6.24%	8.06%	4.90%	4.20%

Notes: [a] IRR that unfavourable, that no result was shown in spread sheet based MPB model

Annexure 46: IRR per LBS and BPA – excluding land value

LBS	Internal Rate of Return (IRR) on capital investment excluding land value (%)			
	Paarl	Worcester	Ashton	R. Cederberge
1	20.41%	16.47%	11.55%	8.28%
2	24.72%	18.69%	12.23%	8.44%
3	3.31%	2.23%	0.11%	-0.29%
4	5.84%	4.91%	3.24%	2.56%
5	8.43%	6.99%	4.86%	3.74%
6	20.18%	16.50%	11.74%	8.38%
7	24.37%	18.44%	12.35%	8.57%
8	4.07%	3.03%	0.73%	0.34%
9	17.10%	13.19%	8.41%	5.90%
10	20.01%	14.48%	8.64%	5.80%
11	0.69%	-0.87%	-3.52%	-2.61%
12	4.31%	3.11%	1.10%	0.78%
13	6.59%	4.88%	2.46%	1.74%
14	17.73%	13.80%	9.11%	6.34%
15	20.74%	15.01%	9.30%	6.20%
16	2.25%	0.88%	-1.94%	-1.53%
17	19.98%	16.07%	11.28%	8.15%
18	24.09%	18.27%	11.90%	8.28%
19	2.74%	1.69%	-0.36%	-0.62%
20	5.60%	4.63%	2.99%	2.37%
21	8.15%	6.69%	4.61%	3.58%
22	19.76%	16.10%	11.48%	8.24%
23	23.75%	18.02%	12.02%	8.41%
24	3.53%	2.53%	0.29%	0.03%
25	21.96%	17.77%	12.44%	8.75%
26	26.56%	19.98%	13.01%	8.90%
27	5.51%	4.35%	1.94%	0.94%
28	6.81%	5.88%	4.11%	3.14%
29	9.80%	8.31%	6.06%	4.52%
30	21.70%	17.62%	12.63%	8.85%
31	26.17%	19.73%	13.13%	9.02%
32	5.69%	4.62%	2.22%	1.30%
33	21.93%	17.63%	12.42%	8.85%
34	26.57%	20.00%	13.16%	9.03%
35	5.99%	4.69%	2.34%	1.33%
36	7.03%	6.06%	4.30%	3.36%
37	9.71%	8.19%	5.93%	4.52%
Minimum	0.69%	-0.87%	-3.52%	-2.61%
Maximum	26.57%	20.00%	13.16%	9.03%
Average	13.62%	10.56%	6.71%	4.69%

Annexure 47: Net Present Value per LBS and BPA

LBS	Biomass procurement areas			
	Paarl	Worcester	Ashton	R. Cederberge
1	R389 047 553	R444 187 194	R358 086 396	R326 318 210
2	R307 193 416	R355 827 319	R281 882 136	R257 141 806
3	R-104 490 634	R-20 969 563	R-91 378 248	R-91 587 549
4	R50 712 243	R115 302 881	R36 166 690	R32 744 163
5	R162 747 067	R239 715 364	R135 215 146	R123 205 558
6	R393 205 218	R447 136 520	R368 221 348	R329 762 641
7	R310 950 667	R353 053 514	R287 306 355	R261 764 773
8	R-80 297 493	R2 317 983	R-72 312 618	R-69 061 742
9	R273 429 890	R354 058 134	R240 571 073	R220 729 749
10	R205 734 966	R276 469 249	R179 426 968	R164 574 835
11	R-226 770 029	R-117 805 363	R-221 043 890	R-202 435 581
12	R-72 128 261	R20 384 754	R-88 910 703	R-79 442 294
13	R2 179 515	R115 880 559	R-28 095 088	R-26 448 008
14	R306 013 410	R383 541 857	R278 087 605	R249 387 963
15	R233 320 237	R296 934 734	R207 817 691	R184 978 904
16	R-183 260 121	R-71 322 588	R-178 509 348	R-163 239 711
17	R378 777 663	R431 314 110	R345 874 323	R317 600 859
18	R297 486 757	R345 719 703	R270 207 305	R248 818 618
19	R-118 033 666	R-35 050 246	R-104 728 121	R-103 028 958
20	R39 997 427	R102 357 562	R23 409 134	R21 723 524
21	R148 493 363	R223 270 055	R119 597 689	R111 059 771
22	R383 060 687	R434 411 958	R356 151 610	R321 156 682
23	R301 303 023	R343 063 269	R275 744 170	R253 542 524
24	R-93 702 039	R-11 574 944	R-85 484 247	R-80 352 513
25	R419 758 133	R475 959 717	R390 855 753	R353 844 604
26	R330 584 012	R379 748 273	R304 567 688	R278 212 551
27	R-53 075 823	R33 975 407	R-36 114 571	R-46 149 743
28	R91 283 151	R157 560 741	R78 651 165	R66 853 956
29	R223 663 797	R303 313 949	R203 492 130	R180 378 012
30	R423 611 657	R475 912 376	R400 761 502	R357 051 342
31	R354 057 841	R376 733 885	R309 783 442	R282 652 330
32	R-41 771 908	R44 244 167	R-26 218 902	R-32 048 383
33	R436 431 277	R492 230 909	R406 090 882	R367 550 968
34	R346 515 506	R395 726 719	R321 826 563	R291 345 006
35	R-35 383 231	R48 581 485	R-22 541 267	R-31 765 927
36	R107 206 701	R172 812 915	R92 857 565	R81 665 670
37	R236 291 763	R313 899 137	R209 042 136	R186 855 512
Minimum	R-226 770 029	R-117 805 363	R-221 043 890	R-202 435 581
Maximum	R436 431 277	R492 230 909	R406 090 882	R367 550 968
Average	R166 057 939	R235 106 046	R149 361 013	R133 658 382

Annexure 48: CAPEX of bioenergy conversion systems per LBS and BPA

LBS	Capital Expenditure (CAPEX) of bioenergy conversion systems including biomass upgrading (ZAR)			
	Paarl	Worcester	Ashton	R. Cederberge
1	R137 754 846	R137 754 846	R137 754 846	R137 754 846
2	R62 922 227	R62 922 227	R62 922 227	R62 922 227
3	R286 292 420	R286 292 420	R286 292 420	R286 292 420
4	R386 570 062	R386 570 062	R386 570 062	R386 570 062
5	R397 982 082	R397 982 082	R397 982 082	R397 982 082
6	R137 754 846	R137 754 846	R137 754 846	R137 754 846
7	R62 922 227	R62 922 227	R62 922 227	R62 922 227
8	R286 292 420	R286 292 420	R286 292 420	R286 292 420
9	R137 754 846	R137 754 846	R137 754 846	R137 754 846
10	R62 922 227	R62 922 227	R62 922 227	R62 922 227
11	R286 292 420	R286 292 420	R286 292 420	R286 292 420
12	R386 570 062	R386 570 062	R386 570 062	R386 570 062
13	R397 982 082	R397 982 082	R397 982 082	R397 982 082
14	R137 754 846	R137 754 846	R137 754 846	R137 754 846
15	R62 922 227	R62 922 227	R62 922 227	R62 922 227
16	R286 292 420	R286 292 420	R286 292 420	R286 292 420
17	R137 754 846	R137 754 846	R137 754 846	R137 754 846
18	R62 922 227	R62 922 227	R62 922 227	R62 922 227
19	R286 292 420	R286 292 420	R286 292 420	R286 292 420
20	R386 570 062	R386 570 062	R386 570 062	R386 570 062
21	R397 982 082	R397 982 082	R397 982 082	R397 982 082
22	R137 754 846	R137 754 846	R137 754 846	R137 754 846
23	R62 922 227	R62 922 227	R62 922 227	R62 922 227
24	R286 292 420	R286 292 420	R286 292 420	R286 292 420
25	R137 754 846	R137 754 846	R137 754 846	R137 754 846
26	R62 922 227	R62 922 227	R62 922 227	R62 922 227
27	R286 292 420	R286 292 420	R286 292 420	R286 292 420
28	R386 570 062	R386 570 062	R386 570 062	R386 570 062
29	R397 982 082	R397 982 082	R397 982 082	R397 982 082
30	R137 754 846	R137 754 846	R137 754 846	R137 754 846
31	R62 922 227	R62 922 227	R62 922 227	R62 922 227
32	R286 292 420	R286 292 420	R286 292 420	R286 292 420
33	R137 754 846	R137 754 846	R137 754 846	R137 754 846
34	R62 922 227	R62 922 227	R62 922 227	R62 922 227
35	R286 292 420	R286 292 420	R286 292 420	R286 292 420
36	R386 570 062	R386 570 062	R386 570 062	R386 570 062
37	R397 982 082	R397 982 082	R397 982 082	R397 982 082

Annexure 49: OPEX of BCSs over period of 20 years per LBS and BPA

LBS	Operational Expenditure (OPEX) of bioenergy conversion systems including biomass upgrading [ZAR]			
	Paarl	Worcester	Ashton	R. Cederberge
1	R127 631 680	R127 631 680	R127 631 680	R127 631 680
2	R66 464 060	R66 464 060	R66 464 060	R66 464 060
3	R250 952 560	R250 952 560	R250 952 560	R250 952 560
4	R309 957 780	R309 957 780	R309 957 780	R309 957 780
5	R281 112 520	R281 112 520	R281 112 520	R281 112 520
6	R127 631 680	R127 631 680	R127 631 680	R127 631 680
7	R66 464 060	R66 464 060	R66 464 060	R66 464 060
8	R250 952 560	R250 952 560	R250 952 560	R250 952 560
9	R127 631 680	R127 631 680	R127 631 680	R127 631 680
10	R66 464 060	R66 464 060	R66 464 060	R66 464 060
11	R250 952 560	R250 952 560	R250 952 560	R250 952 560
12	R309 957 780	R309 957 780	R309 957 780	R309 957 780
13	R281 112 520	R281 112 520	R281 112 520	R281 112 520
14	R127 631 680	R127 631 680	R127 631 680	R127 631 680
15	R66 464 060	R66 464 060	R66 464 060	R66 464 060
16	R250 952 560	R250 952 560	R250 952 560	R250 952 560
17	R127 631 680	R127 631 680	R127 631 680	R127 631 680
18	R66 464 060	R66 464 060	R66 464 060	R66 464 060
19	R250 952 560	R250 952 560	R250 952 560	R250 952 560
20	R309 957 780	R309 957 780	R309 957 780	R309 957 780
21	R281 112 520	R281 112 520	R281 112 520	R281 112 520
22	R127 631 680	R127 631 680	R127 631 680	R127 631 680
23	R66 464 060	R66 464 060	R66 464 060	R66 464 060
24	R250 952 560	R250 952 560	R250 952 560	R250 952 560
25	R127 631 680	R127 631 680	R127 631 680	R127 631 680
26	R66 464 060	R66 464 060	R66 464 060	R66 464 060
27	R250 952 560	R250 952 560	R250 952 560	R250 952 560
28	R309 957 780	R309 957 780	R309 957 780	R309 957 780
29	R281 112 520	R281 112 520	R281 112 520	R281 112 520
30	R127 631 680	R127 631 680	R127 631 680	R127 631 680
31	R66 464 060	R66 464 060	R66 464 060	R66 464 060
32	R250 952 560	R250 952 560	R250 952 560	R250 952 560
33	R127 631 680	R127 631 680	R127 631 680	R127 631 680
34	R66 464 060	R66 464 060	R66 464 060	R66 464 060
35	R250 952 560	R250 952 560	R250 952 560	R250 952 560
36	R309 957 780	R309 957 780	R309 957 780	R309 957 780
37	R281 112 520	R281 112 520	R281 112 520	R281 112 520

Annexure 50: CAPEX other than bioenergy conversion systems per LBS and BPA

LBS	Capital Expenditure (CAPEX) other than bioenergy conversion systems [ZAR]			
	Paarl	Worcester	Ashton	R. Cederberge
1	R181 176 016	R87 573 075	R94 046 857	R72 947 167
2	R153 480 570	R73 839 972	R80 238 501	R60 392 505
3	R235 768 893	R124 412 750	R132 136 085	R107 348 605
4	R212 034 845	R108 762 338	R117 940 645	R92 469 988
5	R271 107 186	R135 947 090	R145 979 454	R114 124 762
6	R169 772 525	R79 538 157	R85 505 365	R66 052 772
7	R147 800 692	R69 337 995	R74 334 424	R56 036 304
8	R215 963 731	R104 309 845	R113 919 377	R87 831 146
9	R208 266 229	R67 217 482	R78 697 555	R46 569 453
10	R172 984 042	R58 560 965	R67 648 893	R40 550 881
11	R238 581 820	R80 469 832	R93 649 608	R54 207 453
12	R218 360 115	R72 328 986	R85 462 636	R49 146 924
13	R288 682 829	R96 332 421	R113 127 919	R65 992 366
14	R187 088 021	R59 462 089	R69 943 797	R39 279 341
15	R164 076 414	R53 465 764	R61 344 816	R36 314 902
16	R225 508 661	R68 826 657	R82 566 084	R44 328 151
17	R190 762 432	R102 289 774	R108 538 839	R82 308 866
18	R163 066 986	R83 426 388	R94 955 200	R69 978 921
19	R250 485 592	R138 904 732	R146 403 351	R121 840 587
20	R221 396 544	R123 254 320	R132 207 911	R106 961 970
21	R285 374 452	R155 344 639	R165 152 286	R128 167 311
22	R179 358 941	R94 254 857	R99 997 348	R75 414 472
23	R157 387 108	R78 924 411	R89 051 124	R65 622 720
24	R230 680 431	R118 801 828	R128 186 643	R102 323 129
25	R160 040 170	R72 557 512	R79 301 577	R52 081 604
26	R137 939 724	R58 794 126	R70 817 938	R45 346 659
27	R194 029 699	R83 438 839	R91 432 458	R65 879 694
28	R172 899 282	R75 747 058	R85 195 649	R58 959 708
29	R229 888 559	R100 868 746	R111 666 393	R73 691 418
30	R148 636 679	R64 027 595	R70 760 086	R45 187 210
31	R132 259 846	R54 292 149	R64 913 862	R40 990 458
32	R182 864 538	R71 975 935	R82 350 750	R55 497 236
33	R134 194 762	R40 367 104	R46 616 169	R25 741 196
34	R115 064 507	R35 424 909	R41 598 721	R21 977 442
35	R158 681 731	R47 100 871	R54 599 490	R30 036 726
36	R146 558 874	R43 061 650	R52 015 241	R26 769 300
37	R196 633 876	R61 249 063	R71 056 710	R39 426 735

Annexure 51: Land value per LBS and BPA

LBS	Total cost for land [ZAR]			
	Paarl	Worcester	Ashton	R. Cederberge
1	R119 900 000	R28 776 000	R35 965 000	R12 946 000
2	R103 200 000	R24 768 000	R30 960 000	R11 145 000
3	R144 000 000	R34 560 000	R43 200 000	R15 552 000
4	R132 600 000	R31 824 000	R39 775 000	R14 319 000
5	R175 050 000	R42 008 000	R52 510 000	R18 903 000
6	R116 200 000	R27 888 000	R34 860 000	R12 550 000
7	R100 050 000	R24 008 000	R30 010 000	R10 804 000
8	R139 600 000	R33 504 000	R41 880 000	R15 076 000
9	R179 250 000	R41 104 000	R51 375 000	R18 495 000
10	R147 450 000	R35 384 000	R44 225 000	R15 921 000
11	R205 750 000	R49 376 000	R61 715 000	R22 218 000
12	R189 450 000	R45 464 000	R56 825 000	R20 456 000
13	R250 050 000	R60 016 000	R75 015 000	R27 005 000
14	R166 000 000	R39 840 000	R49 800 000	R17 928 000
15	R142 950 000	R34 304 000	R42 875 000	R15 434 000
16	R199 450 000	R47 864 000	R59 830 000	R21 538 000
17	R119 900 000	R28 776 000	R35 965 000	R12 946 000
18	R103 200 000	R24 768 000	R30 960 000	R11 145 000
19	R144 000 000	R34 560 000	R43 200 000	R15 552 000
20	R132 600 000	R31 824 000	R39 775 000	R14 319 000
21	R175 050 000	R42 008 000	R52 510 000	R18 903 000
22	R116 200 000	R27 888 000	R34 860 000	R12 550 000
23	R100 050 000	R24 008 000	R30 010 000	R10 804 000
24	R139 600 000	R33 504 000	R41 880 000	R15 076 000
25	R119 900 000	R28 776 000	R35 965 000	R12 946 000
26	R103 200 000	R24 768 000	R30 960 000	R11 145 000
27	R144 000 000	R34 560 000	R43 200 000	R15 552 000
28	R132 600 000	R31 824 000	R39 775 000	R14 319 000
29	R175 050 000	R42 008 000	R52 510 000	R18 903 000
30	R116 200 000	R27 888 000	R34 860 000	R12 550 000
31	R100 050 000	R24 008 000	R30 010 000	R10 804 000
32	R139 600 000	R33 504 000	R41 880 000	R15 076 000
33	R119 900 000	R28 776 000	R35 965 000	R12 946 000
34	R103 200 000	R24 768 000	R30 960 000	R11 145 000
35	R144 000 000	R34 560 000	R43 200 000	R15 552 000
36	R132 600 000	R31 824 000	R39 775 000	R14 319 000
37	R175 050 000	R42 008 000	R52 510 000	R18 903 000

Annexure 52: OPEX other than BCS per LBS and BPA

LBS	Operational Expenditure (OPEX) other than bioenergy conversion systems [ZAR]			
	Paarl	Worcester	Ashton	R. Cederberge
1	R280 615 803	R297 419 784	R357 995 801	R367 331 105
2	R244 303 932	R258 856 864	R311 098 989	R318 950 593
3	R338 753 946	R361 109 135	R425 334 129	R444 381 926
4	R289 022 888	R320 238 289	R390 365 380	R398 399 158
5	R371 453 208	R420 409 326	R506 657 810	R516 698 156
6	R282 716 526	R296 851 865	R346 688 685	R364 503 199
7	R242 807 589	R263 196 706	R305 094 187	R313 299 622
8	R326 132 547	R345 204 100	R414 509 377	R425 842 358
9	R388 093 906	R423 428 972	R515 077 835	R524 174 805
10	R337 656 786	R367 289 244	R446 947 823	R454 761 992
11	R460 336 691	R512 388 716	R614 556 560	R624 777 288
12	R407 113 165	R458 885 228	R563 836 766	R570 827 793
13	R527 367 757	R603 501 843	R735 637 094	R750 435 924
14	R353 587 185	R385 281 593	R464 908 900	R482 402 077
15	R304 600 057	R339 336 250	R407 714 157	R423 653 365
16	R411 743 691	R451 238 147	R557 086 468	R567 328 945
17	R284 343 349	R301 902 332	R362 806 164	R371 968 513
18	R247 537 848	R262 656 053	R315 241 815	R322 939 016
19	R343 340 387	R366 497 971	R431 105 771	R450 034 443
20	R293 180 242	R325 199 855	R395 682 773	R403 604 706
21	R377 033 547	R427 065 853	R513 801 779	R523 570 077
22	R286 357 617	R301 194 878	R351 352 064	R368 995 688
23	R245 947 541	R266 875 831	R309 110 055	R317 169 949
24	R330 583 624	R350 427 260	R420 107 335	R431 325 899
25	R265 200 139	R282 902 842	R344 261 165	R353 411 539
26	R231 037 494	R246 274 574	R299 262 198	R306 975 728
27	R320 236 120	R343 560 746	R408 763 830	R427 673 819
28	R271 877 724	R304 077 146	R375 092 606	R383 005 614
29	R348 923 970	R399 203 203	R486 650 476	R496 405 602
30	R267 782 602	R282 783 197	R333 373 718	R351 018 619
31	R229 926 617	R251 012 051	R293 620 137	R301 679 329
32	R308 157 810	R328 190 876	R398 437 721	R409 633 722
33	R250 069 015	R264 007 197	R321 292 426	R334 962 350
34	R218 020 967	R230 060 126	R279 493 874	R291 115 429
35	R301 994 905	R320 832 884	R381 186 973	R405 428 944
36	R255 135 648	R283 155 463	R349 692 769	R362 526 353
37	R326 845 424	R371 593 429	R453 083 568	R469 459 265

Annexure 53: Employment potential subdivided in income categories per LBS and BPA

LBS	Employment potential subdivided in income categories											
	< R8 000/month				R8 000 – R24 000				> R24 000/month			
	BPA				BPA				BPA			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
1	93	108	122	120	5	4	4	4	2	2	2	2
2	94	106	119	117	5	4	4	4	2	2	2	2
3	140	161	180	179	7	6	5	6	5	5	5	5
4	153	172	188	186	6	6	5	5	5	5	5	5
5	192	215	238	235	7	6	6	6	7	7	7	7
6	70	74	88	87	9	6	6	6	4	4	4	4
7	74	77	89	88	8	5	5	5	4	4	4	4
8	106	112	132	130	12	8	8	8	7	7	7	7
9	181	210	241	225	3	2	2	2	2	2	2	2
10	170	194	221	207	3	2	2	2	2	2	2	2
11	265	306	350	327	4	3	3	3	5	5	5	5
12	260	296	333	314	3	3	2	3	5	5	5	5
13	333	379	429	403	4	3	3	3	7	7	7	7
14	153	171	201	186	7	4	4	4	4	4	4	4
15	145	160	186	173	6	3	3	3	4	4	4	4
16	224	250	293	271	9	5	5	5	7	7	7	7
17	86	98	111	112	7	6	7	6	2	2	2	2
18	87	98	110	110	7	6	6	6	2	2	2	2
19	129	148	165	166	10	9	9	9	5	5	5	5
20	143	160	175	175	8	8	8	7	5	5	5	5
21	179	200	221	221	10	10	10	10	7	7	7	7
22	62	65	78	78	11	8	9	8	4	4	4	4
23	67	69	80	80	10	7	7	7	4	4	4	4
24	95	100	118	118	15	11	11	11	7	7	7	7
25	94	108	122	121	5	5	5	4	2	2	2	2
26	95	107	119	118	5	4	5	4	2	2	2	2
27	141	161	180	180	7	6	6	6	5	5	5	5
28	154	172	188	186	6	6	5	5	5	5	5	5
29	192	215	238	236	7	7	7	7	7	7	7	7
30	70	75	88	87	9	7	7	6	4	4	4	4
31	74	77	89	88	8	5	6	5	4	4	4	4
32	107	113	132	130	12	8	9	8	7	7	7	7
33	61	66	78	78	5	4	3	3	2	2	2	2
34	65	69	81	81	4	3	3	3	2	2	2	2
35	93	101	119	120	7	6	5	6	5	5	5	5
36	112	119	134	134	5	5	4	4	5	5	5	5
37	137	146	167	167	6	5	5	5	7	7	7	7

Annexure 54: Normalised, un-weighted scores for BPA I

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria				
	IRR (25 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact	
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (25 yrs)	OPEX (25 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years
1	4.61%	4.05%	3.90%	2.98%	3.11%	1.21%	1.32%	0.00%	3.94%	3.41%	3.37%	3.19%	2.28%
2	4.81%	5.22%	5.45%	3.75%	3.56%	1.25%	1.32%	0.00%	5.41%	4.91%	4.06%	3.48%	2.29%
3	0.00%	1.74%	1.38%	1.47%	2.37%	2.99%	2.65%	3.80%	0.78%	0.19%	1.47%	2.42%	2.29%
4	1.43%	0.18%	0.69%	2.13%	3.00%	3.49%	1.99%	3.80%	1.94%	1.35%	2.14%	3.12%	2.32%
5	2.04%	0.00%	0.00%	0.49%	1.96%	4.96%	2.65%	6.33%	0.30%	3.75%	1.46%	2.48%	6.03%
6	4.65%	4.05%	3.90%	3.30%	3.08%	0.34%	3.97%	1.27%	3.53%	3.40%	3.26%	2.63%	2.31%
7	4.87%	5.22%	5.45%	3.91%	3.58%	0.49%	3.31%	1.27%	5.05%	4.90%	3.97%	3.00%	2.31%
8	0.16%	1.74%	1.38%	2.02%	2.53%	1.71%	5.96%	5.06%	0.20%	0.17%	1.33%	1.62%	2.32%
9	3.27%	4.05%	3.90%	2.23%	1.75%	4.55%	0.00%	0.00%	3.82%	3.31%	2.46%	2.10%	2.29%
10	3.27%	5.22%	5.45%	3.21%	2.39%	4.13%	0.00%	0.00%	5.30%	4.82%	3.27%	2.53%	2.29%
11	0.00%	1.74%	1.38%	1.39%	0.84%	7.73%	0.66%	3.80%	0.60%	0.04%	0.18%	0.86%	2.30%
12	0.58%	0.18%	0.69%	1.95%	1.51%	7.54%	0.00%	3.80%	1.79%	1.23%	1.03%	1.81%	2.33%
13	1.08%	0.00%	0.00%	0.00%	0.00%	10.31%	0.66%	6.33%	0.11%	3.58%	0.00%	0.73%	6.04%
14	3.51%	4.05%	3.90%	2.82%	2.19%	3.49%	2.65%	1.27%	8.26%	3.28%	4.45%	3.84%	0.00%
15	3.54%	5.22%	5.45%	3.46%	2.80%	3.18%	1.99%	1.27%	4.93%	4.79%	3.19%	2.01%	2.31%
16	0.00%	1.74%	1.38%	1.75%	1.46%	6.18%	3.97%	5.06%	0.00%	0.00%	0.05%	0.00%	2.32%
17	4.52%	4.05%	3.90%	2.72%	3.06%	0.95%	2.65%	0.00%	3.93%	3.39%	3.79%	3.46%	2.21%
18	4.71%	5.22%	5.45%	3.49%	3.52%	0.99%	2.65%	0.00%	5.40%	4.89%	4.43%	3.71%	2.22%
19	0.00%	1.74%	1.38%	1.06%	2.32%	2.58%	4.64%	3.80%	0.76%	0.16%	2.08%	2.80%	2.18%
20	1.36%	0.18%	0.69%	1.87%	2.95%	3.11%	3.31%	3.80%	1.93%	1.33%	2.66%	3.44%	2.23%
21	1.96%	0.00%	0.00%	0.09%	1.89%	4.47%	4.64%	6.33%	0.28%	3.72%	2.15%	2.92%	5.91%
22	4.57%	4.05%	3.90%	3.03%	3.03%	0.04%	5.30%	1.27%	3.52%	3.37%	3.68%	2.89%	2.24%
23	4.76%	5.22%	5.45%	3.64%	3.54%	0.23%	4.64%	1.27%	5.04%	4.87%	4.32%	3.19%	2.24%
24	0.00%	1.74%	1.38%	1.61%	2.48%	1.29%	7.95%	5.06%	0.18%	0.14%	1.91%	1.97%	2.22%
25	4.88%	4.05%	3.90%	3.57%	3.30%	1.25%	1.32%	0.00%	3.85%	3.32%	3.73%	3.23%	2.19%
26	5.08%	5.22%	5.45%	4.18%	3.73%	1.29%	1.32%	0.00%	5.33%	4.83%	4.37%	3.52%	2.20%
27	0.47%	1.74%	1.38%	2.63%	2.61%	3.03%	2.65%	3.80%	0.65%	0.06%	1.99%	2.48%	2.15%
28	1.73%	0.18%	0.69%	3.21%	3.22%	3.52%	1.99%	3.80%	1.83%	1.24%	2.58%	3.17%	2.20%
29	2.41%	0.00%	0.00%	1.63%	2.25%	4.96%	2.65%	6.33%	0.16%	3.60%	2.05%	2.56%	5.87%
30	4.93%	4.05%	3.90%	3.89%	3.27%	0.34%	3.97%	1.27%	3.44%	3.30%	3.61%	2.67%	2.22%
31	5.14%	5.22%	5.45%	4.34%	3.74%	0.49%	3.31%	1.27%	4.97%	4.81%	4.27%	3.00%	2.23%
32	0.60%	1.74%	1.38%	2.94%	2.76%	1.74%	5.96%	5.06%	0.07%	0.04%	1.82%	1.66%	2.19%
33	4.95%	4.05%	3.90%	4.29%	3.49%	0.00%	1.32%	0.00%	3.98%	3.44%	3.75%	3.61%	2.29%
34	5.18%	5.22%	5.45%	4.82%	3.89%	0.15%	0.66%	0.00%	5.44%	4.93%	4.38%	3.81%	2.29%
35	0.68%	1.74%	1.38%	3.61%	2.84%	1.21%	2.65%	3.80%	0.84%	0.23%	2.02%	3.00%	2.30%
36	1.83%	0.18%	0.69%	3.95%	3.43%	1.93%	1.32%	3.80%	2.01%	1.41%	2.62%	3.77%	2.34%
37	2.44%	0.00%	0.00%	2.56%	2.52%	2.88%	1.99%	6.33%	0.40%	3.82%	2.10%	3.35%	6.06%
sum	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Annexure 55: Normalised, un-weighted scores for BPA II

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria				
	IRR (27 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact	
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (27 yrs)	OPEX (27 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years
1	4.07%	4.05%	3.90%	2.51%	3.15%	1.41%	1.52%	0.00%	4.15%	3.97%	3.36%	3.28%	0.76%
2	4.37%	5.22%	5.45%	3.02%	3.55%	1.34%	1.52%	0.00%	5.68%	5.46%	4.00%	3.53%	0.79%
3	0.82%	1.74%	1.38%	1.14%	2.49%	3.14%	3.03%	3.80%	0.84%	0.77%	1.61%	2.54%	0.72%
4	1.61%	0.18%	0.69%	1.72%	2.92%	3.50%	3.03%	3.80%	2.03%	1.91%	2.21%	3.06%	0.82%
5	2.07%	0.00%	0.00%	0.72%	1.88%	4.91%	3.03%	6.33%	0.30%	0.18%	1.57%	2.42%	16.50%
6	4.10%	4.05%	3.90%	2.80%	3.16%	0.29%	3.03%	1.27%	3.72%	3.96%	3.27%	2.74%	0.89%
7	4.35%	5.22%	5.45%	3.18%	3.50%	0.39%	2.27%	1.27%	5.31%	5.45%	3.92%	3.07%	0.90%
8	1.02%	1.74%	1.38%	1.89%	2.66%	1.54%	4.55%	5.06%	0.23%	0.75%	1.48%	1.78%	0.89%
9	3.24%	4.05%	3.90%	3.26%	1.85%	4.75%	0.00%	0.00%	4.01%	3.85%	2.39%	2.06%	0.70%
10	3.38%	5.22%	5.45%	3.58%	2.43%	4.23%	0.00%	0.00%	5.56%	5.36%	3.16%	2.48%	0.74%
11	0.00%	1.74%	1.38%	2.77%	0.94%	7.89%	0.76%	3.80%	0.63%	0.60%	0.22%	0.81%	0.63%
12	1.11%	0.18%	0.69%	3.07%	1.49%	7.57%	0.76%	3.80%	1.85%	1.77%	1.02%	1.59%	0.75%
13	1.49%	0.00%	0.00%	2.18%	0.00%	10.28%	0.76%	6.33%	0.07%	0.00%	0.00%	0.48%	16.41%
14	3.39%	4.05%	3.90%	3.55%	2.25%	3.47%	1.52%	1.27%	3.56%	3.83%	2.31%	1.49%	0.80%
15	3.51%	5.22%	5.45%	3.77%	2.72%	3.11%	0.76%	1.27%	5.18%	5.34%	3.09%	1.99%	0.82%
16	0.43%	1.74%	1.38%	3.20%	1.57%	6.06%	2.27%	5.06%	0.00%	0.57%	0.11%	0.00%	0.77%
17	3.99%	4.05%	3.90%	1.96%	3.10%	1.08%	3.03%	0.00%	4.14%	3.95%	3.83%	3.58%	0.35%
18	4.29%	5.22%	5.45%	2.66%	3.51%	1.08%	3.03%	0.00%	5.67%	5.44%	4.40%	3.79%	0.43%
19	0.69%	1.74%	1.38%	0.61%	2.44%	2.72%	5.30%	3.80%	0.82%	0.73%	2.26%	2.97%	0.13%
20	1.55%	0.18%	0.69%	1.19%	2.86%	3.11%	4.55%	3.80%	2.01%	1.87%	2.77%	3.43%	0.31%
21	2.00%	0.00%	0.00%	0.00%	1.82%	4.42%	6.06%	6.33%	0.28%	0.14%	2.31%	2.91%	15.83%
22	4.01%	4.05%	3.90%	2.26%	3.11%	0.00%	4.55%	1.27%	3.71%	3.93%	3.72%	3.04%	0.48%
23	4.27%	5.22%	5.45%	2.83%	3.46%	0.13%	3.79%	1.27%	5.30%	5.42%	4.31%	3.32%	0.55%
24	0.90%	1.74%	1.38%	1.35%	2.60%	1.15%	6.82%	5.06%	0.21%	0.71%	2.11%	2.19%	0.32%
25	4.32%	4.05%	3.90%	3.06%	3.30%	1.41%	2.27%	0.00%	4.06%	3.87%	3.77%	3.36%	0.26%
26	4.61%	5.22%	5.45%	3.57%	3.68%	1.38%	1.52%	0.00%	5.60%	5.37%	4.35%	3.61%	0.35%
27	1.30%	1.74%	1.38%	2.66%	2.68%	3.14%	3.03%	3.80%	0.70%	0.63%	2.18%	2.66%	0.00%
28	1.84%	0.18%	0.69%	2.94%	3.08%	3.50%	3.03%	3.80%	1.91%	1.79%	2.70%	3.17%	0.20%
29	2.37%	0.00%	0.00%	2.02%	2.10%	4.91%	3.79%	6.33%	0.15%	0.03%	2.21%	2.56%	15.69%
30	4.31%	4.05%	3.90%	3.38%	3.30%	0.33%	3.79%	1.27%	3.63%	3.86%	3.66%	2.82%	0.39%
31	4.59%	5.22%	5.45%	3.74%	3.63%	0.39%	2.27%	1.27%	5.23%	5.36%	4.26%	3.13%	0.47%
32	1.38%	1.74%	1.38%	3.08%	2.83%	1.57%	4.55%	5.06%	0.09%	0.61%	2.03%	1.89%	0.20%
33	4.32%	4.05%	3.90%	4.25%	3.49%	0.03%	1.52%	0.00%	4.21%	4.01%	3.80%	3.81%	0.84%
34	4.64%	5.22%	5.45%	4.44%	3.84%	0.13%	0.76%	0.00%	5.73%	5.49%	4.37%	3.98%	0.86%
35	1.40%	1.74%	1.38%	4.00%	2.91%	1.18%	3.03%	3.80%	0.92%	0.82%	2.22%	3.29%	0.83%
36	1.89%	0.18%	0.69%	4.15%	3.30%	1.77%	2.27%	3.80%	2.11%	1.96%	2.74%	3.78%	0.95%
37	2.36%	0.00%	0.00%	3.48%	2.39%	2.65%	2.27%	6.33%	0.41%	0.26%	2.27%	3.37%	16.67%
sum	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Annexure 56: Normalised, un-weighted scores for BPA III

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria				
	IRR (30 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact	
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (30 yrs)	OPEX (30 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years
1	3.93%	4.05%	3.83%	2.61%	3.14%	1.33%	1.54%	0.00%	4.15%	3.97%	3.27%	0.85%	3.31%
2	4.01%	5.22%	5.35%	3.11%	3.53%	1.24%	1.54%	0.00%	5.67%	5.43%	3.52%	0.92%	3.89%
3	1.02%	1.74%	1.36%	1.21%	2.58%	3.08%	2.31%	3.80%	0.86%	0.80%	2.56%	0.67%	1.69%
4	1.96%	0.18%	0.68%	1.73%	2.87%	3.32%	2.31%	3.80%	2.04%	1.92%	3.01%	0.81%	2.24%
5	2.35%	0.00%	0.00%	0.70%	1.90%	4.82%	3.08%	6.33%	0.32%	0.21%	2.35%	16.36%	1.63%
6	3.99%	4.05%	3.83%	2.92%	3.23%	0.30%	3.08%	1.27%	3.73%	3.95%	2.80%	0.98%	3.23%
7	4.06%	5.22%	5.35%	3.33%	3.58%	0.33%	2.31%	1.27%	5.30%	5.42%	3.11%	1.04%	3.82%
8	1.19%	1.74%	1.36%	1.88%	2.67%	1.63%	4.62%	5.06%	0.26%	0.78%	1.89%	0.86%	1.58%
9	3.09%	4.05%	3.83%	3.17%	1.83%	4.91%	0.00%	0.00%	3.98%	3.83%	1.96%	0.60%	2.29%
10	3.08%	5.22%	5.35%	3.58%	2.40%	4.31%	0.00%	0.00%	5.52%	5.32%	2.38%	0.70%	3.02%
11	0.00%	1.74%	1.36%	2.62%	1.01%	8.20%	0.77%	3.80%	0.62%	0.61%	0.70%	0.32%	0.25%
12	1.34%	0.18%	0.68%	2.92%	1.43%	7.69%	0.00%	3.80%	1.84%	1.76%	1.46%	0.53%	1.01%
13	1.66%	0.00%	0.00%	1.91%	0.00%	10.58%	0.77%	6.33%	0.05%	0.00%	0.32%	15.99%	0.00%
14	3.28%	4.05%	3.83%	3.49%	2.25%	3.71%	1.54%	1.27%	3.54%	3.81%	1.47%	0.71%	2.23%
15	3.25%	5.22%	5.35%	3.81%	2.73%	3.26%	0.77%	1.27%	5.14%	5.30%	1.96%	0.80%	2.96%
16	0.43%	1.74%	1.36%	3.03%	1.48%	6.48%	2.31%	5.06%	0.00%	0.57%	0.00%	0.48%	0.15%
17	3.87%	4.05%	3.83%	2.08%	3.10%	0.99%	3.85%	0.00%	4.13%	3.94%	3.58%	0.47%	3.79%
18	3.94%	5.22%	5.35%	2.57%	3.49%	0.96%	3.08%	0.00%	5.65%	5.41%	3.78%	0.59%	4.30%
19	0.89%	1.74%	1.36%	0.69%	2.53%	2.62%	5.38%	3.80%	0.84%	0.76%	3.00%	0.13%	2.37%
20	1.90%	0.18%	0.68%	1.21%	2.83%	2.92%	4.62%	3.80%	2.01%	1.88%	3.38%	0.35%	2.82%
21	2.29%	0.00%	0.00%	0.00%	1.84%	4.31%	6.15%	6.33%	0.29%	0.16%	2.88%	15.76%	2.40%
22	3.93%	4.05%	3.83%	2.39%	3.19%	0.00%	5.38%	1.27%	3.71%	3.92%	3.10%	0.61%	3.69%
23	3.98%	5.22%	5.35%	2.79%	3.55%	0.06%	3.85%	1.27%	5.28%	5.40%	3.36%	0.72%	4.22%
24	1.08%	1.74%	1.36%	1.36%	2.62%	1.21%	6.92%	5.06%	0.24%	0.74%	2.32%	0.34%	2.23%
25	4.13%	4.05%	3.83%	3.15%	3.25%	1.33%	2.31%	0.00%	4.05%	3.86%	3.39%	0.38%	3.73%
26	4.19%	5.22%	5.35%	3.46%	3.63%	1.24%	2.31%	0.00%	5.58%	5.35%	3.62%	0.51%	4.26%
27	1.48%	1.74%	1.36%	2.70%	2.72%	3.08%	3.08%	3.80%	0.72%	0.66%	2.73%	0.00%	2.29%
28	2.18%	0.18%	0.68%	2.93%	3.00%	3.32%	2.31%	3.80%	1.92%	1.80%	3.15%	0.24%	2.76%
29	2.64%	0.00%	0.00%	1.96%	2.07%	4.82%	3.85%	6.33%	0.16%	0.05%	2.56%	15.61%	2.31%
30	4.19%	4.05%	5.66%	3.46%	3.34%	0.30%	3.85%	1.27%	3.63%	3.86%	2.91%	0.53%	3.64%
31	4.23%	5.22%	5.35%	3.68%	3.67%	0.33%	3.08%	1.27%	5.22%	5.34%	3.20%	0.64%	4.18%
32	1.56%	1.74%	1.36%	3.04%	2.80%	1.63%	5.38%	5.06%	0.13%	0.64%	2.05%	0.21%	2.16%
33	4.15%	4.05%	3.83%	4.35%	3.44%	0.00%	0.77%	0.00%	4.21%	4.00%	3.83%	0.95%	3.76%
34	4.24%	5.22%	5.35%	4.53%	3.79%	0.09%	0.77%	0.00%	5.72%	5.47%	3.99%	1.00%	4.28%
35	1.60%	1.74%	1.36%	4.05%	2.95%	1.24%	2.31%	3.80%	0.95%	0.85%	3.35%	0.81%	2.34%
36	2.24%	0.18%	0.68%	4.15%	3.21%	1.69%	1.54%	3.80%	2.12%	1.97%	3.73%	0.95%	2.80%
37	2.63%	0.00%	0.00%	3.45%	2.35%	2.68%	2.31%	6.33%	0.43%	0.28%	3.33%	16.56%	2.37%
sum	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Annexure 57: Normalised, un-weighted scores for BPA IV

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria				
	IRR (35 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact	
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (35 yrs)	OPEX (35 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years
1	4.02%	4.05%	3.90%	2.33%	3.16%	1.33%	1.60%	0.00%	4.16%	3.97%	3.31%	0.64%	3.39%
2	4.05%	5.22%	5.45%	2.85%	3.56%	1.24%	1.60%	0.00%	5.68%	5.45%	3.55%	0.71%	4.03%
3	0.88%	1.74%	1.38%	0.88%	2.52%	3.21%	3.20%	3.80%	0.84%	0.77%	2.55%	0.45%	1.59%
4	1.97%	0.18%	0.69%	1.50%	2.90%	3.43%	2.40%	3.80%	2.02%	1.90%	3.04%	0.61%	2.20%
5	2.39%	0.00%	0.00%	0.59%	1.93%	4.99%	3.20%	6.33%	0.30%	0.18%	2.38%	17.07%	1.54%
6	4.05%	4.05%	3.90%	2.62%	3.18%	0.29%	3.20%	1.27%	3.73%	3.96%	2.78%	0.78%	3.29%
7	4.10%	5.22%	5.45%	3.04%	3.60%	0.32%	2.40%	1.27%	5.31%	5.44%	3.09%	0.83%	3.95%
8	1.11%	1.74%	1.38%	1.70%	2.67%	1.65%	4.80%	5.06%	0.23%	0.75%	1.79%	0.65%	1.46%
9	3.13%	4.05%	3.90%	3.44%	1.86%	4.67%	0.00%	0.00%	4.01%	3.85%	2.07%	0.42%	2.42%
10	3.08%	5.22%	5.45%	3.69%	2.44%	4.10%	0.00%	0.00%	5.56%	5.36%	2.51%	0.53%	3.21%
11	0.00%	1.74%	1.38%	3.11%	1.04%	7.91%	0.80%	3.80%	0.63%	0.61%	0.80%	0.14%	0.23%
12	1.29%	0.18%	0.69%	3.33%	1.48%	7.50%	0.80%	3.80%	1.85%	1.76%	1.56%	0.35%	1.03%
13	1.63%	0.00%	0.00%	2.62%	0.00%	10.32%	0.80%	6.33%	0.07%	0.00%	0.43%	16.73%	0.00%
14	3.29%	4.05%	3.90%	3.74%	2.21%	3.43%	1.60%	1.27%	3.56%	3.83%	1.51%	0.54%	2.34%
15	3.22%	5.22%	5.45%	3.87%	2.69%	3.02%	0.80%	1.27%	5.18%	5.33%	2.02%	0.63%	3.14%
16	0.40%	1.74%	1.38%	3.53%	1.51%	6.13%	2.40%	5.06%	0.00%	0.57%	0.00%	0.30%	0.11%
17	3.97%	4.05%	3.90%	1.93%	3.12%	1.08%	3.20%	0.00%	4.14%	3.95%	3.60%	0.42%	3.84%
18	3.99%	5.22%	5.45%	2.45%	3.52%	1.02%	3.20%	0.00%	5.67%	5.43%	3.80%	0.52%	4.42%
19	0.75%	1.74%	1.38%	0.27%	2.48%	2.80%	5.60%	3.80%	0.82%	0.74%	2.96%	0.14%	2.23%
20	1.90%	0.18%	0.69%	0.89%	2.86%	3.08%	4.00%	3.80%	2.00%	1.87%	3.39%	0.34%	2.75%
21	2.33%	0.00%	0.00%	0.00%	1.87%	4.54%	6.40%	6.33%	0.27%	0.14%	2.85%	16.72%	2.27%
22	4.01%	4.05%	3.90%	2.22%	3.14%	0.00%	4.80%	1.27%	3.71%	3.93%	3.06%	0.57%	3.73%
23	4.04%	5.22%	5.45%	2.63%	3.57%	0.06%	4.00%	1.27%	5.30%	5.42%	3.34%	0.65%	4.33%
24	1.00%	1.74%	1.38%	1.09%	2.63%	1.27%	7.20%	5.06%	0.21%	0.72%	2.20%	0.35%	2.08%
25	4.18%	4.05%	3.90%	3.20%	3.27%	1.37%	1.60%	0.00%	4.06%	3.87%	3.38%	0.33%	3.78%
26	4.21%	5.22%	5.45%	3.49%	3.65%	1.27%	1.60%	0.00%	5.60%	5.37%	3.62%	0.44%	4.37%
27	1.33%	1.74%	1.38%	2.62%	2.66%	3.24%	3.20%	3.80%	0.70%	0.63%	2.65%	0.00%	2.15%
28	2.18%	0.18%	0.69%	2.91%	3.03%	3.43%	2.40%	3.80%	1.90%	1.78%	3.13%	0.22%	2.67%
29	2.67%	0.00%	0.00%	2.29%	2.09%	5.02%	4.00%	6.33%	0.14%	0.03%	2.50%	16.56%	2.17%
30	4.22%	4.05%	3.90%	3.49%	3.29%	0.29%	3.20%	1.27%	3.63%	3.86%	2.85%	0.48%	3.67%
31	4.26%	5.22%	5.45%	3.67%	3.70%	0.32%	2.40%	1.27%	5.23%	5.36%	3.16%	0.57%	4.28%
32	1.46%	1.74%	1.38%	3.06%	2.81%	1.65%	4.80%	5.06%	0.10%	0.62%	1.90%	0.22%	2.00%
33	4.22%	4.05%	3.90%	4.31%	3.42%	0.00%	0.80%	0.00%	4.21%	4.01%	3.84%	0.73%	3.81%
34	4.26%	5.22%	5.45%	4.47%	3.78%	0.10%	0.80%	0.00%	5.74%	5.49%	4.01%	0.79%	4.40%
35	1.48%	1.74%	1.38%	4.13%	2.84%	1.33%	3.20%	3.80%	0.92%	0.83%	3.31%	0.58%	2.19%
36	2.26%	0.18%	0.69%	4.27%	3.20%	1.78%	1.60%	3.80%	2.10%	1.95%	3.74%	0.74%	2.72%
37	2.68%	0.00%	0.00%	3.74%	2.32%	2.83%	2.40%	6.33%	0.40%	0.25%	3.30%	17.25%	2.23%
sum	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Annexure 58: Normalised to sum one, but un-weighted scores for BPA I

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria					Sum
	IRR (25 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (25 yrs)	OPEX (25 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	0.35%	0.31%	0.30%	0.23%	0.24%	0.09%	0.10%	0.00%	0.30%	0.26%	0.26%	0.25%	0.18%	2.78%
2	0.37%	0.40%	0.42%	0.29%	0.27%	0.10%	0.10%	0.00%	0.42%	0.38%	0.31%	0.27%	0.18%	3.23%
3	0.00%	0.13%	0.11%	0.11%	0.18%	0.23%	0.20%	0.29%	0.06%	0.01%	0.11%	0.19%	0.18%	2.08%
4	0.11%	0.01%	0.05%	0.16%	0.23%	0.27%	0.15%	0.29%	0.15%	0.10%	0.16%	0.24%	0.18%	2.26%
5	0.16%	0.00%	0.00%	0.04%	0.15%	0.38%	0.20%	0.49%	0.02%	0.29%	0.11%	0.19%	0.46%	2.51%
6	0.36%	0.31%	0.30%	0.25%	0.24%	0.03%	0.31%	0.10%	0.27%	0.26%	0.25%	0.20%	0.18%	2.96%
7	0.37%	0.40%	0.42%	0.30%	0.28%	0.04%	0.25%	0.10%	0.39%	0.38%	0.31%	0.23%	0.18%	3.37%
8	0.01%	0.13%	0.11%	0.16%	0.19%	0.13%	0.46%	0.39%	0.02%	0.01%	0.10%	0.12%	0.18%	2.29%
9	0.25%	0.31%	0.30%	0.17%	0.13%	0.35%	0.00%	0.00%	0.29%	0.25%	0.19%	0.16%	0.18%	2.51%
10	0.25%	0.40%	0.42%	0.25%	0.18%	0.32%	0.00%	0.00%	0.41%	0.37%	0.25%	0.19%	0.18%	2.96%
11	0.00%	0.13%	0.11%	0.11%	0.06%	0.59%	0.05%	0.29%	0.05%	0.00%	0.01%	0.07%	0.18%	1.94%
12	0.04%	0.01%	0.05%	0.15%	0.12%	0.58%	0.00%	0.29%	0.14%	0.09%	0.08%	0.14%	0.18%	2.03%
13	0.08%	0.00%	0.00%	0.00%	0.00%	0.79%	0.05%	0.49%	0.01%	0.28%	0.00%	0.06%	0.46%	2.26%
14	0.27%	0.31%	0.30%	0.22%	0.17%	0.27%	0.20%	0.10%	0.64%	0.25%	0.34%	0.30%	0.00%	3.11%
15	0.27%	0.40%	0.42%	0.27%	0.22%	0.24%	0.15%	0.10%	0.38%	0.37%	0.25%	0.15%	0.18%	3.14%
16	0.00%	0.13%	0.11%	0.13%	0.11%	0.48%	0.31%	0.39%	0.00%	0.00%	0.00%	0.00%	0.18%	2.13%
17	0.35%	0.31%	0.30%	0.21%	0.24%	0.07%	0.20%	0.00%	0.30%	0.26%	0.29%	0.27%	0.17%	2.88%
18	0.36%	0.40%	0.42%	0.27%	0.27%	0.08%	0.20%	0.00%	0.42%	0.38%	0.34%	0.29%	0.17%	3.32%
19	0.00%	0.13%	0.11%	0.08%	0.18%	0.20%	0.36%	0.29%	0.06%	0.01%	0.16%	0.22%	0.17%	2.23%
20	0.10%	0.01%	0.05%	0.14%	0.23%	0.24%	0.25%	0.29%	0.15%	0.10%	0.20%	0.26%	0.17%	2.36%
21	0.15%	0.00%	0.00%	0.01%	0.15%	0.34%	0.36%	0.49%	0.02%	0.29%	0.17%	0.22%	0.45%	2.67%
22	0.35%	0.31%	0.30%	0.23%	0.23%	0.00%	0.41%	0.10%	0.27%	0.26%	0.28%	0.22%	0.17%	3.05%
23	0.37%	0.40%	0.42%	0.28%	0.27%	0.02%	0.36%	0.10%	0.39%	0.37%	0.33%	0.25%	0.17%	3.46%
24	0.00%	0.13%	0.11%	0.12%	0.19%	0.10%	0.61%	0.39%	0.01%	0.01%	0.15%	0.15%	0.17%	2.43%
25	0.38%	0.31%	0.30%	0.27%	0.25%	0.10%	0.10%	0.00%	0.30%	0.26%	0.29%	0.25%	0.17%	2.88%
26	0.39%	0.40%	0.42%	0.32%	0.29%	0.10%	0.10%	0.00%	0.41%	0.37%	0.34%	0.27%	0.17%	3.32%
27	0.04%	0.13%	0.11%	0.20%	0.20%	0.23%	0.20%	0.29%	0.05%	0.00%	0.15%	0.19%	0.17%	2.26%
28	0.13%	0.01%	0.05%	0.25%	0.25%	0.27%	0.15%	0.29%	0.14%	0.10%	0.20%	0.24%	0.17%	2.41%
29	0.19%	0.00%	0.00%	0.13%	0.17%	0.38%	0.20%	0.49%	0.01%	0.28%	0.16%	0.20%	0.45%	2.69%
30	0.38%	0.31%	0.30%	0.30%	0.25%	0.03%	0.31%	0.10%	0.26%	0.25%	0.28%	0.21%	0.17%	3.06%
31	0.40%	0.40%	0.42%	0.33%	0.29%	0.04%	0.25%	0.10%	0.38%	0.37%	0.33%	0.23%	0.17%	3.45%
32	0.05%	0.13%	0.11%	0.23%	0.21%	0.13%	0.46%	0.39%	0.01%	0.00%	0.14%	0.13%	0.17%	2.44%
33	0.38%	0.31%	0.30%	0.33%	0.27%	0.00%	0.10%	0.00%	0.31%	0.26%	0.29%	0.28%	0.18%	2.91%
34	0.40%	0.40%	0.42%	0.37%	0.30%	0.01%	0.05%	0.00%	0.42%	0.38%	0.34%	0.29%	0.18%	3.29%
35	0.05%	0.13%	0.11%	0.28%	0.22%	0.09%	0.20%	0.29%	0.06%	0.02%	0.16%	0.23%	0.18%	2.29%
36	0.14%	0.01%	0.05%	0.30%	0.26%	0.15%	0.10%	0.29%	0.15%	0.11%	0.20%	0.29%	0.18%	2.38%
37	0.19%	0.00%	0.00%	0.20%	0.19%	0.22%	0.15%	0.49%	0.03%	0.29%	0.16%	0.26%	0.47%	2.66%
sum	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	100.00%

Annexure 59: Normalised to sum one, but un-weighted scores for BPA II

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria					Sum
	IRR (27 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (27 yrs)	OPEX (27 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	0.31%	0.31%	0.30%	0.19%	0.24%	0.11%	0.12%	0.00%	0.32%	0.31%	0.26%	0.25%	0.06%	2.78%
2	0.34%	0.40%	0.42%	0.23%	0.27%	0.10%	0.12%	0.00%	0.44%	0.42%	0.31%	0.27%	0.06%	3.38%
3	0.06%	0.13%	0.11%	0.09%	0.19%	0.24%	0.23%	0.29%	0.06%	0.06%	0.12%	0.20%	0.06%	1.85%
4	0.12%	0.01%	0.05%	0.13%	0.22%	0.27%	0.23%	0.29%	0.16%	0.15%	0.17%	0.24%	0.06%	2.11%
5	0.16%	0.00%	0.00%	0.06%	0.14%	0.38%	0.23%	0.49%	0.02%	0.01%	0.12%	0.19%	1.27%	3.07%
6	0.32%	0.31%	0.30%	0.22%	0.24%	0.02%	0.23%	0.10%	0.29%	0.30%	0.25%	0.21%	0.07%	2.86%
7	0.33%	0.40%	0.42%	0.24%	0.27%	0.03%	0.17%	0.10%	0.41%	0.42%	0.30%	0.24%	0.07%	3.41%
8	0.08%	0.13%	0.11%	0.15%	0.20%	0.12%	0.35%	0.39%	0.02%	0.06%	0.11%	0.14%	0.07%	1.92%
9	0.25%	0.31%	0.30%	0.25%	0.14%	0.37%	0.00%	0.00%	0.31%	0.30%	0.18%	0.16%	0.05%	2.62%
10	0.26%	0.40%	0.42%	0.28%	0.19%	0.33%	0.00%	0.00%	0.43%	0.41%	0.24%	0.19%	0.06%	3.20%
11	0.00%	0.13%	0.11%	0.21%	0.07%	0.61%	0.06%	0.29%	0.05%	0.05%	0.02%	0.06%	0.05%	1.71%
12	0.09%	0.01%	0.05%	0.24%	0.11%	0.58%	0.06%	0.29%	0.14%	0.14%	0.08%	0.12%	0.06%	1.97%
13	0.11%	0.00%	0.00%	0.17%	0.00%	0.79%	0.06%	0.49%	0.01%	0.00%	0.00%	0.04%	1.26%	2.92%
14	0.26%	0.31%	0.30%	0.27%	0.17%	0.27%	0.12%	0.10%	0.27%	0.29%	0.18%	0.11%	0.06%	2.72%
15	0.27%	0.40%	0.42%	0.29%	0.21%	0.24%	0.06%	0.10%	0.40%	0.41%	0.24%	0.15%	0.06%	3.25%
16	0.03%	0.13%	0.11%	0.25%	0.12%	0.47%	0.17%	0.39%	0.00%	0.04%	0.01%	0.00%	0.06%	1.78%
17	0.31%	0.31%	0.30%	0.15%	0.24%	0.08%	0.23%	0.00%	0.32%	0.30%	0.29%	0.28%	0.03%	2.84%
18	0.33%	0.40%	0.42%	0.20%	0.27%	0.08%	0.23%	0.00%	0.44%	0.42%	0.34%	0.29%	0.03%	3.46%
19	0.05%	0.13%	0.11%	0.05%	0.19%	0.21%	0.41%	0.29%	0.06%	0.06%	0.17%	0.23%	0.01%	1.97%
20	0.12%	0.01%	0.05%	0.09%	0.22%	0.24%	0.35%	0.29%	0.15%	0.14%	0.21%	0.26%	0.02%	2.18%
21	0.15%	0.00%	0.00%	0.00%	0.14%	0.34%	0.47%	0.49%	0.02%	0.01%	0.18%	0.22%	1.22%	3.24%
22	0.31%	0.31%	0.30%	0.17%	0.24%	0.00%	0.35%	0.10%	0.29%	0.30%	0.29%	0.23%	0.04%	2.92%
23	0.33%	0.40%	0.42%	0.22%	0.27%	0.01%	0.29%	0.10%	0.41%	0.42%	0.33%	0.26%	0.04%	3.48%
24	0.07%	0.13%	0.11%	0.10%	0.20%	0.09%	0.52%	0.39%	0.02%	0.05%	0.16%	0.17%	0.02%	2.04%
25	0.33%	0.31%	0.30%	0.24%	0.25%	0.11%	0.17%	0.00%	0.31%	0.30%	0.29%	0.26%	0.02%	2.89%
26	0.35%	0.40%	0.42%	0.27%	0.28%	0.11%	0.12%	0.00%	0.43%	0.41%	0.33%	0.28%	0.03%	3.44%
27	0.10%	0.13%	0.11%	0.20%	0.21%	0.24%	0.23%	0.29%	0.05%	0.05%	0.17%	0.20%	0.00%	1.99%
28	0.14%	0.01%	0.05%	0.23%	0.24%	0.27%	0.23%	0.29%	0.15%	0.14%	0.21%	0.24%	0.02%	2.22%
29	0.18%	0.00%	0.00%	0.16%	0.16%	0.38%	0.29%	0.49%	0.01%	0.00%	0.17%	0.20%	1.21%	3.24%
30	0.33%	0.31%	0.30%	0.26%	0.25%	0.03%	0.29%	0.10%	0.28%	0.30%	0.28%	0.22%	0.03%	2.98%
31	0.35%	0.40%	0.42%	0.29%	0.28%	0.03%	0.17%	0.10%	0.40%	0.41%	0.33%	0.24%	0.04%	3.46%
32	0.11%	0.13%	0.11%	0.24%	0.22%	0.12%	0.35%	0.39%	0.01%	0.05%	0.16%	0.15%	0.02%	2.03%
33	0.33%	0.31%	0.30%	0.33%	0.27%	0.00%	0.12%	0.00%	0.32%	0.31%	0.29%	0.29%	0.06%	2.94%
34	0.36%	0.40%	0.42%	0.34%	0.30%	0.01%	0.06%	0.00%	0.44%	0.42%	0.34%	0.31%	0.07%	3.45%
35	0.11%	0.13%	0.11%	0.31%	0.22%	0.09%	0.23%	0.29%	0.07%	0.06%	0.17%	0.25%	0.06%	2.12%
36	0.15%	0.01%	0.05%	0.32%	0.25%	0.14%	0.17%	0.29%	0.16%	0.15%	0.21%	0.29%	0.07%	2.28%
37	0.18%	0.00%	0.00%	0.27%	0.18%	0.20%	0.17%	0.49%	0.03%	0.02%	0.17%	0.26%	1.28%	3.27%
sum	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	100.00%

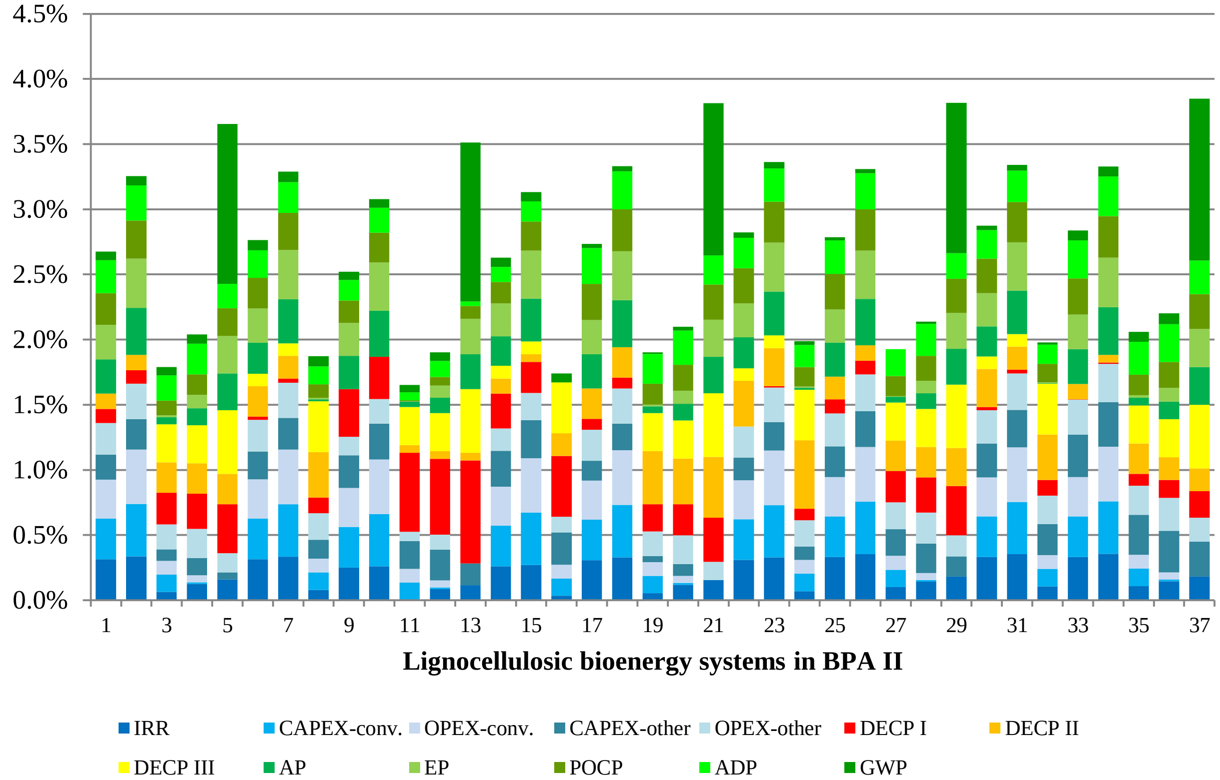
Annexure 60: Normalised to sum one, but un-weighted scores for BPA III

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria					Sum
	IRR (30 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (30 yrs)	OPEX (30 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	0.30%	0.31%	0.29%	0.20%	0.24%	0.10%	0.12%	0.00%	0.32%	0.31%	0.25%	0.07%	0.25%	2.77%
2	0.31%	0.40%	0.41%	0.24%	0.27%	0.10%	0.12%	0.00%	0.44%	0.42%	0.27%	0.07%	0.30%	3.34%
3	0.08%	0.13%	0.10%	0.09%	0.20%	0.24%	0.18%	0.29%	0.07%	0.06%	0.20%	0.05%	0.13%	1.82%
4	0.15%	0.01%	0.05%	0.13%	0.22%	0.26%	0.18%	0.29%	0.16%	0.15%	0.23%	0.06%	0.17%	2.07%
5	0.18%	0.00%	0.00%	0.05%	0.15%	0.37%	0.24%	0.49%	0.02%	0.02%	0.18%	1.26%	0.13%	3.08%
6	0.31%	0.31%	0.29%	0.22%	0.25%	0.02%	0.24%	0.10%	0.29%	0.30%	0.22%	0.08%	0.25%	2.87%
7	0.31%	0.40%	0.41%	0.26%	0.28%	0.03%	0.18%	0.10%	0.41%	0.42%	0.24%	0.08%	0.29%	3.39%
8	0.09%	0.13%	0.10%	0.14%	0.21%	0.13%	0.36%	0.39%	0.02%	0.06%	0.15%	0.07%	0.12%	1.96%
9	0.24%	0.31%	0.29%	0.24%	0.14%	0.38%	0.00%	0.00%	0.31%	0.29%	0.15%	0.05%	0.18%	2.58%
10	0.24%	0.40%	0.41%	0.28%	0.18%	0.33%	0.00%	0.00%	0.42%	0.41%	0.18%	0.05%	0.23%	3.14%
11	0.00%	0.13%	0.10%	0.20%	0.08%	0.63%	0.06%	0.29%	0.05%	0.05%	0.05%	0.02%	0.02%	1.69%
12	0.10%	0.01%	0.05%	0.22%	0.11%	0.59%	0.00%	0.29%	0.14%	0.14%	0.11%	0.04%	0.08%	1.89%
13	0.13%	0.00%	0.00%	0.15%	0.00%	0.81%	0.06%	0.49%	0.00%	0.00%	0.02%	1.23%	0.00%	2.89%
14	0.25%	0.31%	0.29%	0.27%	0.17%	0.29%	0.12%	0.10%	0.27%	0.29%	0.11%	0.05%	0.17%	2.70%
15	0.25%	0.40%	0.41%	0.29%	0.21%	0.25%	0.06%	0.10%	0.40%	0.41%	0.15%	0.06%	0.23%	3.22%
16	0.03%	0.13%	0.10%	0.23%	0.11%	0.50%	0.18%	0.39%	0.00%	0.04%	0.00%	0.04%	0.01%	1.78%
17	0.30%	0.31%	0.29%	0.16%	0.24%	0.08%	0.30%	0.00%	0.32%	0.30%	0.28%	0.04%	0.29%	2.90%
18	0.30%	0.40%	0.41%	0.20%	0.27%	0.07%	0.24%	0.00%	0.43%	0.42%	0.29%	0.05%	0.33%	3.41%
19	0.07%	0.13%	0.10%	0.05%	0.19%	0.20%	0.41%	0.29%	0.06%	0.06%	0.23%	0.01%	0.18%	2.01%
20	0.15%	0.01%	0.05%	0.09%	0.22%	0.22%	0.36%	0.29%	0.15%	0.14%	0.26%	0.03%	0.22%	2.20%
21	0.18%	0.00%	0.00%	0.00%	0.14%	0.33%	0.47%	0.49%	0.02%	0.01%	0.22%	1.21%	0.18%	3.26%
22	0.30%	0.31%	0.29%	0.18%	0.25%	0.00%	0.41%	0.10%	0.29%	0.30%	0.24%	0.05%	0.28%	3.01%
23	0.31%	0.40%	0.41%	0.21%	0.27%	0.00%	0.30%	0.10%	0.41%	0.42%	0.26%	0.06%	0.32%	3.46%
24	0.08%	0.13%	0.10%	0.10%	0.20%	0.09%	0.53%	0.39%	0.02%	0.06%	0.18%	0.03%	0.17%	2.09%
25	0.32%	0.31%	0.29%	0.24%	0.25%	0.10%	0.18%	0.00%	0.31%	0.30%	0.26%	0.03%	0.29%	2.88%
26	0.32%	0.40%	0.41%	0.27%	0.28%	0.10%	0.18%	0.00%	0.43%	0.41%	0.28%	0.04%	0.33%	3.44%
27	0.11%	0.13%	0.10%	0.21%	0.21%	0.24%	0.24%	0.29%	0.06%	0.05%	0.21%	0.00%	0.18%	2.03%
28	0.17%	0.01%	0.05%	0.23%	0.23%	0.26%	0.18%	0.29%	0.15%	0.14%	0.24%	0.02%	0.21%	2.17%
29	0.20%	0.00%	0.00%	0.15%	0.16%	0.37%	0.30%	0.49%	0.01%	0.00%	0.20%	1.20%	0.18%	3.26%
30	0.32%	0.31%	0.44%	0.27%	0.26%	0.02%	0.30%	0.10%	0.28%	0.30%	0.22%	0.04%	0.28%	3.13%
31	0.33%	0.40%	0.41%	0.28%	0.28%	0.03%	0.24%	0.10%	0.40%	0.41%	0.25%	0.05%	0.32%	3.49%
32	0.12%	0.13%	0.10%	0.23%	0.22%	0.13%	0.41%	0.39%	0.01%	0.05%	0.16%	0.02%	0.17%	2.14%
33	0.32%	0.31%	0.29%	0.33%	0.26%	0.00%	0.06%	0.00%	0.32%	0.31%	0.29%	0.07%	0.29%	2.87%
34	0.33%	0.40%	0.41%	0.35%	0.29%	0.01%	0.06%	0.00%	0.44%	0.42%	0.31%	0.08%	0.33%	3.42%
35	0.12%	0.13%	0.10%	0.31%	0.23%	0.10%	0.18%	0.29%	0.07%	0.07%	0.26%	0.06%	0.18%	2.10%
36	0.17%	0.01%	0.05%	0.32%	0.25%	0.13%	0.12%	0.29%	0.16%	0.15%	0.29%	0.07%	0.22%	2.23%
37	0.20%	0.00%	0.00%	0.27%	0.18%	0.21%	0.18%	0.49%	0.03%	0.02%	0.26%	1.27%	0.18%	3.29%
sum	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	100.00%

Annexure 61: Normalised to sum one, but un-weighted scores for BPA IV

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria					Sum
	IRR (35 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (35 yrs)	OPEX (35 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	0.31%	0.31%	0.30%	0.18%	0.24%	0.10%	0.12%	0.00%	0.32%	0.31%	0.25%	0.05%	0.26%	2.76%
2	0.31%	0.40%	0.42%	0.22%	0.27%	0.10%	0.12%	0.00%	0.44%	0.42%	0.27%	0.05%	0.31%	3.34%
3	0.07%	0.13%	0.11%	0.07%	0.19%	0.25%	0.25%	0.29%	0.06%	0.06%	0.20%	0.03%	0.12%	1.83%
4	0.15%	0.01%	0.05%	0.12%	0.22%	0.26%	0.18%	0.29%	0.16%	0.15%	0.23%	0.05%	0.17%	2.05%
5	0.18%	0.00%	0.00%	0.05%	0.15%	0.38%	0.25%	0.49%	0.02%	0.01%	0.18%	1.31%	0.12%	3.15%
6	0.31%	0.31%	0.30%	0.20%	0.24%	0.02%	0.25%	0.10%	0.29%	0.30%	0.21%	0.06%	0.25%	2.85%
7	0.32%	0.40%	0.42%	0.23%	0.28%	0.02%	0.18%	0.10%	0.41%	0.42%	0.24%	0.06%	0.30%	3.39%
8	0.09%	0.13%	0.11%	0.13%	0.21%	0.13%	0.37%	0.39%	0.02%	0.06%	0.14%	0.05%	0.11%	1.92%
9	0.24%	0.31%	0.30%	0.26%	0.14%	0.36%	0.00%	0.00%	0.31%	0.30%	0.16%	0.03%	0.19%	2.60%
10	0.24%	0.40%	0.42%	0.28%	0.19%	0.32%	0.00%	0.00%	0.43%	0.41%	0.19%	0.04%	0.25%	3.16%
11	0.00%	0.13%	0.11%	0.24%	0.08%	0.61%	0.06%	0.29%	0.05%	0.05%	0.06%	0.01%	0.02%	1.71%
12	0.10%	0.01%	0.05%	0.26%	0.11%	0.58%	0.06%	0.29%	0.14%	0.14%	0.12%	0.03%	0.08%	1.97%
13	0.13%	0.00%	0.00%	0.20%	0.00%	0.79%	0.06%	0.49%	0.01%	0.00%	0.03%	1.29%	0.00%	2.99%
14	0.25%	0.31%	0.30%	0.29%	0.17%	0.26%	0.12%	0.10%	0.27%	0.29%	0.12%	0.04%	0.18%	2.71%
15	0.25%	0.40%	0.42%	0.30%	0.21%	0.23%	0.06%	0.10%	0.40%	0.41%	0.16%	0.05%	0.24%	3.22%
16	0.03%	0.13%	0.11%	0.27%	0.12%	0.47%	0.18%	0.39%	0.00%	0.04%	0.00%	0.02%	0.01%	1.78%
17	0.31%	0.31%	0.30%	0.15%	0.24%	0.08%	0.25%	0.00%	0.32%	0.30%	0.28%	0.03%	0.30%	2.86%
18	0.31%	0.40%	0.42%	0.19%	0.27%	0.08%	0.25%	0.00%	0.44%	0.42%	0.29%	0.04%	0.34%	3.44%
19	0.06%	0.13%	0.11%	0.02%	0.19%	0.22%	0.43%	0.29%	0.06%	0.06%	0.23%	0.01%	0.17%	1.98%
20	0.15%	0.01%	0.05%	0.07%	0.22%	0.24%	0.31%	0.29%	0.15%	0.14%	0.26%	0.03%	0.21%	2.13%
21	0.18%	0.00%	0.00%	0.00%	0.14%	0.35%	0.49%	0.49%	0.02%	0.01%	0.22%	1.29%	0.17%	3.36%
22	0.31%	0.31%	0.30%	0.17%	0.24%	0.00%	0.37%	0.10%	0.29%	0.30%	0.24%	0.04%	0.29%	2.95%
23	0.31%	0.40%	0.42%	0.20%	0.27%	0.00%	0.31%	0.10%	0.41%	0.42%	0.26%	0.05%	0.33%	3.48%
24	0.08%	0.13%	0.11%	0.08%	0.20%	0.10%	0.55%	0.39%	0.02%	0.06%	0.17%	0.03%	0.16%	2.07%
25	0.32%	0.31%	0.30%	0.25%	0.25%	0.11%	0.12%	0.00%	0.31%	0.30%	0.26%	0.03%	0.29%	2.85%
26	0.32%	0.40%	0.42%	0.27%	0.28%	0.10%	0.12%	0.00%	0.43%	0.41%	0.28%	0.03%	0.34%	3.41%
27	0.10%	0.13%	0.11%	0.20%	0.20%	0.25%	0.25%	0.29%	0.05%	0.05%	0.20%	0.00%	0.17%	2.01%
28	0.17%	0.01%	0.05%	0.22%	0.23%	0.26%	0.18%	0.29%	0.15%	0.14%	0.24%	0.02%	0.21%	2.18%
29	0.21%	0.00%	0.00%	0.18%	0.16%	0.39%	0.31%	0.49%	0.01%	0.00%	0.19%	1.27%	0.17%	3.37%
30	0.32%	0.31%	0.30%	0.27%	0.25%	0.02%	0.25%	0.10%	0.28%	0.30%	0.22%	0.04%	0.28%	2.94%
31	0.33%	0.40%	0.42%	0.28%	0.28%	0.02%	0.18%	0.10%	0.40%	0.41%	0.24%	0.04%	0.33%	3.45%
32	0.11%	0.13%	0.11%	0.24%	0.22%	0.13%	0.37%	0.39%	0.01%	0.05%	0.15%	0.02%	0.15%	2.06%
33	0.32%	0.31%	0.30%	0.33%	0.26%	0.00%	0.06%	0.00%	0.32%	0.31%	0.30%	0.06%	0.29%	2.87%
34	0.33%	0.40%	0.42%	0.34%	0.29%	0.01%	0.06%	0.00%	0.44%	0.42%	0.31%	0.06%	0.34%	3.42%
35	0.11%	0.13%	0.11%	0.32%	0.22%	0.10%	0.25%	0.29%	0.07%	0.06%	0.25%	0.04%	0.17%	2.13%
36	0.17%	0.01%	0.05%	0.33%	0.25%	0.14%	0.12%	0.29%	0.16%	0.15%	0.29%	0.06%	0.21%	2.23%
37	0.21%	0.00%	0.00%	0.29%	0.18%	0.22%	0.18%	0.49%	0.03%	0.02%	0.25%	1.33%	0.17%	3.36%
sum	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	7.69%	100.00%

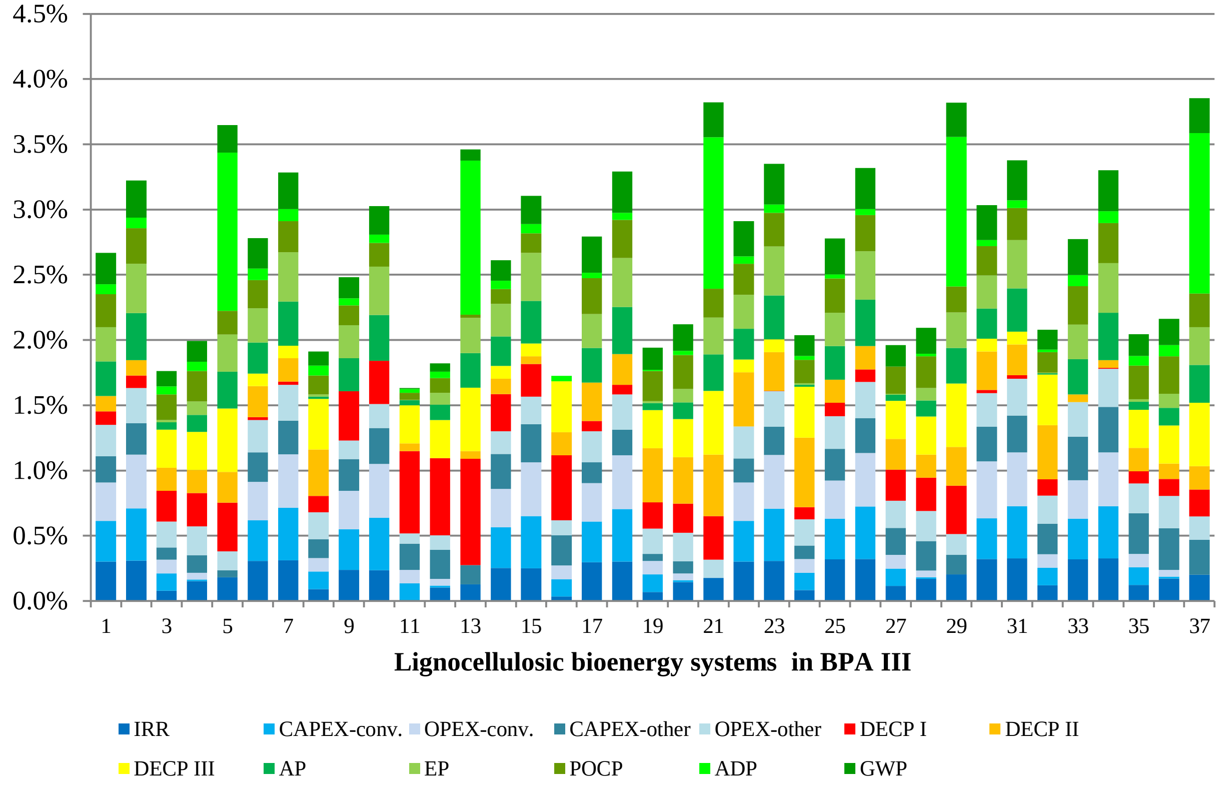
Annexure 62: Aggregated, unweighted scores of LBSs for BPA II



Notes:

IRR	Internal Rate of Return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than biomass upgrading and conversion technologies
DECP I	Direct Employment Creation Potential with income less than R8 000/month
DECP II	Direct Employment Creation Potential with income between R8 000 – R24 000/month
DECP III	Direct Employment Creation Potential with income more than R24 000/month
AP	Acidification Potential
EP	Eutrophication Potential
POCP	Photochemical Ozone Creation Potential
ADP	Abiotic Depletion Potential
GWP	Global Warming Potential

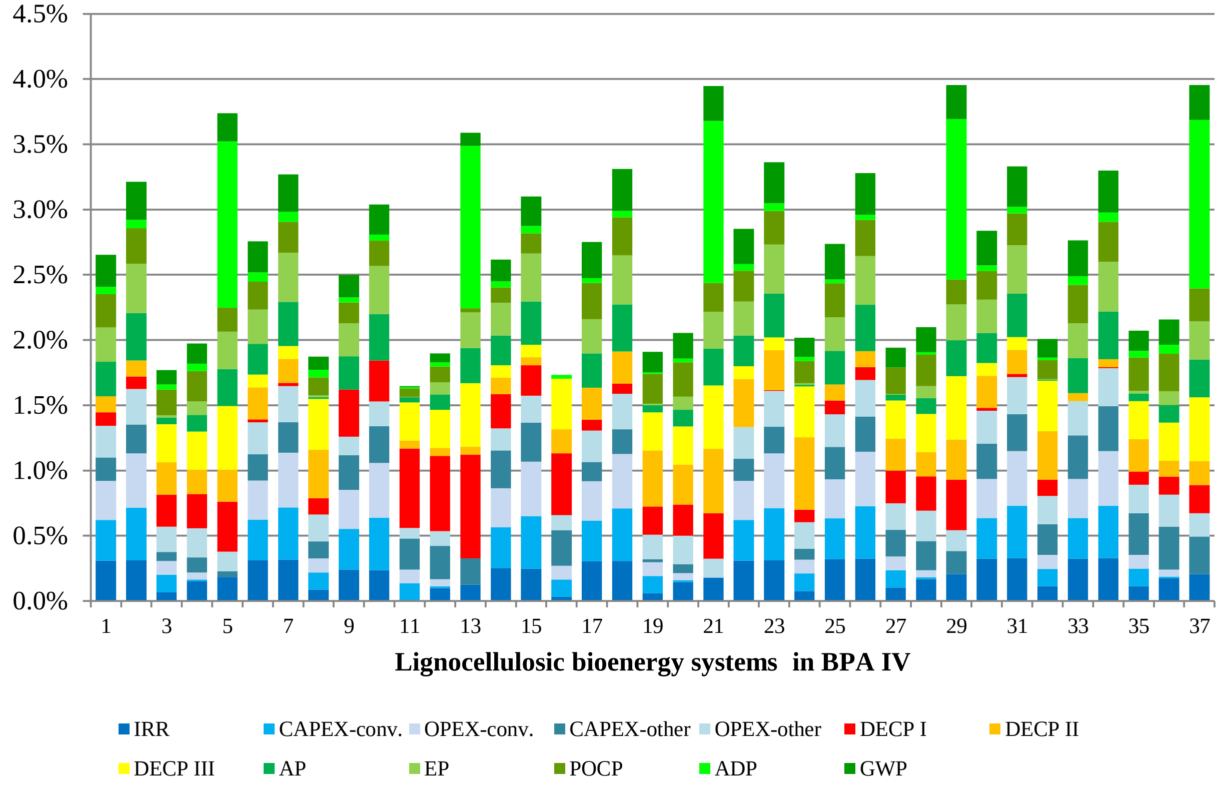
Annexure 63: Aggregated, unweighted scores of LBSs for BPA III



Notes:

IRR	Internal Rate of Return on capital investment
CAPEX-conv.	Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv.	Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other	Capital expenditure other than biomass upgrading and conversion technologies
OPEX-other	Operational expenditure other than biomass upgrading and conversion technologies
DECP I	Direct Employment Creation Potential with income less than R8 000/month
DECP II	Direct Employment Creation Potential with income between R8 000 – R24 000/month
DECP III	Direct Employment Creation Potential with income more than R24 000/month
AP	Acidification Potential
EP	Eutrophication Potential
POCP	Photochemical Ozone Creation Potential
ADP	Abiotic Depletion Potential
GWP	Global Warming Potential

Annexure 64: Aggregated, unweighted scores of LBSs for BPA IV



Notes:

IRR Internal Rate of Return on capital investment
CAPEX-conv. Capital expenditure of biomass upgrading and conversion technologies
OPEX-conv. Operational expenditure of biomass upgrading and conversion technologies
CAPEX-other Capital expenditure other than biomass upgrading and conversion technologies
OPEX-other Operational expenditure other than biomass upgrading and conversion technologies
DECP I Direct Employment Creation Potential with income less than R8 000/month
DECP II Direct Employment Creation Potential with income between R8 000 – R24 000/month
DECP III Direct Employment Creation Potential with income more than R24 000/month
AP Acidification Potential
EP Eutrophication Potential
POCP Photochemical Ozone Creation Potential
ADP Abiotic Depletion Potential
GWP Global Warming Potential

Annexure 65: Participants of MCDA workshop

	Name	Organisation/Company	Position/background
1	Mr J. Buckle	South African National Biodiversity Institute (SANBI)	Freshwater programme: Eastern Cape Provincial coordinator
2	Mr R. Burger	Department of Economics, Stellenbosch University	Senior lecturer/labour economics, technical expert
3	Mrs G. Daniels	Cape Winelands District Municipality	Manager: local development
4	Mr G. Forsyth	Council for Scientific and Industrial Research (CSIR)/	AHP expert, MCDA facilitator
4	Dr W. De Lange	Council for Scientific and Industrial Research (CSIR)/Natural Resources and the Environment Unit	Senior environmental economist/Specialist in MCDA
5	Prof J. Du Toit	Institute of Futures Research (IFR), Stellenbosch University	Former member of IFR, pensioner, energy expert
6	Ms H. Fourie	Department of Agriculture: Western Cape	Senior agricultural economist: resource economics
7	Mr C Goosen	Department of Agriculture: Western Cape	Agricultural economist: Production economics
8	Mr A. Greeff	Standardbank	Head of agriculture unit
9	Mr J.D. Kirsten		Farmer and owner, entrepreneur
10	Prof TE Kleynhans	Department of Agricultural Economics, Stellenbosch University	Associate Professor, Resource Economist, Co-facilitator
11	Ms N. Peacock	Cape Winelands District Municipality	Assistant manager: local development
12	Mr T. Roos	Rust en Vrede grape farm	Farmer and owner
13	Dr A. Rozanov	Department of Soil Science, Stellenbosch University	Soil scientist, technical expert
14	Mr. D. Roussow	Nedbank	Head of agriculture unit
15	Mr C. Von Doderer	Department of Agricultural Economics, Stellenbosch University	PhD student, facilitator

Annexure 66: Normalised, weighted scores for BPA I

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria					Sum
	IRR (25 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (25 yrs)	OPEX (25 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	1.98%	0.27%	0.09%	0.04%	0.19%	0.22%	0.06%	0.00%	0.13%	0.28%	0.05%	0.07%	0.01%	3.29%
2	2.07%	0.35%	0.12%	0.05%	0.22%	0.23%	0.06%	0.00%	0.18%	0.41%	0.06%	0.08%	0.01%	3.54%
3	0.00%	0.12%	0.03%	0.02%	0.15%	0.55%	0.12%	0.08%	0.03%	0.02%	0.02%	0.05%	0.01%	1.48%
4	0.62%	0.01%	0.02%	0.03%	0.19%	0.64%	0.09%	0.08%	0.07%	0.11%	0.03%	0.07%	0.01%	2.10%
5	0.88%	0.00%	0.00%	0.01%	0.12%	0.90%	0.12%	0.13%	0.01%	0.31%	0.02%	0.06%	0.02%	2.60%
6	2.00%	0.27%	0.09%	0.04%	0.19%	0.06%	0.19%	0.03%	0.12%	0.28%	0.04%	0.06%	0.01%	3.28%
7	2.09%	0.35%	0.12%	0.05%	0.22%	0.09%	0.16%	0.03%	0.17%	0.41%	0.05%	0.07%	0.01%	3.53%
8	0.07%	0.12%	0.03%	0.02%	0.16%	0.31%	0.28%	0.10%	0.01%	0.01%	0.02%	0.04%	0.01%	1.47%
9	1.41%	0.27%	0.09%	0.03%	0.11%	0.83%	0.00%	0.00%	0.13%	0.28%	0.03%	0.05%	0.01%	3.13%
10	1.41%	0.35%	0.12%	0.04%	0.15%	0.75%	0.00%	0.00%	0.18%	0.40%	0.04%	0.06%	0.01%	3.23%
11	0.00%	0.12%	0.03%	0.02%	0.05%	1.41%	0.03%	0.08%	0.02%	0.00%	0.00%	0.02%	0.01%	2.10%
12	0.25%	0.01%	0.02%	0.02%	0.09%	1.37%	0.00%	0.08%	0.06%	0.10%	0.01%	0.04%	0.01%	2.24%
13	0.46%	0.00%	0.00%	0.00%	0.00%	1.88%	0.03%	0.13%	0.00%	0.30%	0.00%	0.02%	0.02%	2.88%
14	1.51%	0.27%	0.09%	0.03%	0.14%	0.64%	0.12%	0.03%	0.28%	0.27%	0.06%	0.09%	0.00%	3.25%
15	1.52%	0.35%	0.12%	0.04%	0.17%	0.58%	0.09%	0.03%	0.17%	0.40%	0.04%	0.05%	0.01%	3.30%
16	0.00%	0.12%	0.03%	0.02%	0.09%	1.13%	0.19%	0.10%	0.00%	0.00%	0.00%	0.00%	0.01%	2.00%
17	1.94%	0.27%	0.09%	0.03%	0.19%	0.17%	0.12%	0.00%	0.13%	0.28%	0.05%	0.08%	0.01%	3.27%
18	2.02%	0.35%	0.12%	0.04%	0.22%	0.18%	0.12%	0.00%	0.18%	0.41%	0.06%	0.08%	0.01%	3.51%
19	0.00%	0.12%	0.03%	0.01%	0.14%	0.47%	0.22%	0.08%	0.03%	0.01%	0.03%	0.06%	0.01%	1.50%
20	0.58%	0.01%	0.02%	0.02%	0.18%	0.57%	0.16%	0.08%	0.07%	0.11%	0.04%	0.08%	0.01%	2.06%
21	0.84%	0.00%	0.00%	0.00%	0.12%	0.81%	0.22%	0.13%	0.01%	0.31%	0.03%	0.07%	0.02%	2.58%
22	1.96%	0.27%	0.09%	0.04%	0.19%	0.01%	0.25%	0.03%	0.12%	0.28%	0.05%	0.06%	0.01%	3.25%
23	2.05%	0.35%	0.12%	0.04%	0.22%	0.04%	0.22%	0.03%	0.17%	0.41%	0.06%	0.07%	0.01%	3.50%
24	0.00%	0.12%	0.03%	0.02%	0.15%	0.23%	0.37%	0.10%	0.01%	0.01%	0.03%	0.04%	0.01%	1.43%
25	2.10%	0.27%	0.09%	0.04%	0.20%	0.23%	0.06%	0.00%	0.13%	0.28%	0.05%	0.07%	0.01%	3.44%
26	2.19%	0.35%	0.12%	0.05%	0.23%	0.23%	0.06%	0.00%	0.18%	0.40%	0.06%	0.08%	0.01%	3.69%
27	0.20%	0.12%	0.03%	0.03%	0.16%	0.55%	0.12%	0.08%	0.02%	0.00%	0.03%	0.06%	0.01%	1.72%
28	0.74%	0.01%	0.02%	0.04%	0.20%	0.64%	0.09%	0.08%	0.06%	0.10%	0.04%	0.07%	0.01%	2.26%
29	1.04%	0.00%	0.00%	0.02%	0.14%	0.90%	0.12%	0.13%	0.01%	0.30%	0.03%	0.06%	0.02%	2.80%
30	2.12%	0.27%	0.09%	0.05%	0.20%	0.06%	0.19%	0.03%	0.12%	0.28%	0.05%	0.06%	0.01%	3.42%
31	2.21%	0.35%	0.12%	0.05%	0.23%	0.09%	0.16%	0.03%	0.17%	0.40%	0.06%	0.07%	0.01%	3.66%
32	0.26%	0.12%	0.03%	0.04%	0.17%	0.32%	0.28%	0.10%	0.00%	0.00%	0.03%	0.04%	0.01%	1.70%
33	2.13%	0.27%	0.09%	0.05%	0.22%	0.00%	0.06%	0.00%	0.13%	0.29%	0.05%	0.08%	0.01%	3.27%
34	2.23%	0.35%	0.12%	0.06%	0.24%	0.03%	0.03%	0.00%	0.18%	0.41%	0.06%	0.09%	0.01%	3.51%
35	0.29%	0.12%	0.03%	0.04%	0.18%	0.22%	0.12%	0.08%	0.03%	0.02%	0.03%	0.07%	0.01%	1.52%
36	0.79%	0.01%	0.02%	0.05%	0.21%	0.35%	0.06%	0.08%	0.07%	0.12%	0.04%	0.08%	0.01%	2.02%
37	1.05%	0.00%	0.00%	0.03%	0.16%	0.52%	0.09%	0.13%	0.01%	0.32%	0.03%	0.08%	0.02%	2.45%
Sum	43.03%	6.69%	2.23%	1.23%	6.17%	18.22%	4.70%	2.02%	3.38%	8.34%	1.37%	2.24%	0.37%	100.00%

Annexure 67: Normalised, weighted scores for BPA II

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria					Sum
	IRR (27 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (27 yrs)	OPEX (27 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	1.75%	0.27%	0.09%	0.03%	0.19%	0.26%	0.07%	0.00%	0.14%	0.33%	0.05%	0.07%	0.00%	3.26%
2	1.88%	0.35%	0.12%	0.04%	0.22%	0.24%	0.07%	0.00%	0.19%	0.46%	0.05%	0.08%	0.00%	3.71%
3	0.35%	0.12%	0.03%	0.01%	0.15%	0.57%	0.14%	0.08%	0.03%	0.06%	0.02%	0.06%	0.00%	1.63%
4	0.69%	0.01%	0.02%	0.02%	0.18%	0.64%	0.14%	0.08%	0.07%	0.16%	0.03%	0.07%	0.00%	2.11%
5	0.89%	0.00%	0.00%	0.01%	0.12%	0.89%	0.14%	0.13%	0.01%	0.02%	0.02%	0.05%	0.06%	2.34%
6	1.76%	0.27%	0.09%	0.03%	0.19%	0.05%	0.14%	0.03%	0.13%	0.33%	0.04%	0.06%	0.00%	3.14%
7	1.87%	0.35%	0.12%	0.04%	0.22%	0.07%	0.11%	0.03%	0.18%	0.45%	0.05%	0.07%	0.00%	3.56%
8	0.44%	0.12%	0.03%	0.02%	0.16%	0.28%	0.21%	0.10%	0.01%	0.06%	0.02%	0.04%	0.00%	1.50%
9	1.39%	0.27%	0.09%	0.04%	0.11%	0.87%	0.00%	0.00%	0.14%	0.32%	0.03%	0.05%	0.00%	3.31%
10	1.45%	0.35%	0.12%	0.04%	0.15%	0.77%	0.00%	0.00%	0.19%	0.45%	0.04%	0.06%	0.00%	3.62%
11	0.00%	0.12%	0.03%	0.03%	0.06%	1.44%	0.04%	0.08%	0.02%	0.05%	0.00%	0.02%	0.00%	1.88%
12	0.48%	0.01%	0.02%	0.04%	0.09%	1.38%	0.04%	0.08%	0.06%	0.15%	0.01%	0.04%	0.00%	2.39%
13	0.64%	0.00%	0.00%	0.03%	0.00%	1.87%	0.04%	0.13%	0.00%	0.00%	0.00%	0.01%	0.06%	2.78%
14	1.46%	0.27%	0.09%	0.04%	0.14%	0.63%	0.07%	0.03%	0.12%	0.32%	0.03%	0.03%	0.00%	3.24%
15	1.51%	0.35%	0.12%	0.05%	0.17%	0.57%	0.04%	0.03%	0.17%	0.44%	0.04%	0.04%	0.00%	3.54%
16	0.19%	0.12%	0.03%	0.04%	0.10%	1.10%	0.11%	0.10%	0.00%	0.05%	0.00%	0.00%	0.00%	1.83%
17	1.72%	0.27%	0.09%	0.02%	0.19%	0.20%	0.14%	0.00%	0.14%	0.33%	0.05%	0.08%	0.00%	3.23%
18	1.85%	0.35%	0.12%	0.03%	0.22%	0.20%	0.14%	0.00%	0.19%	0.45%	0.06%	0.09%	0.00%	3.70%
19	0.30%	0.12%	0.03%	0.01%	0.15%	0.50%	0.25%	0.08%	0.03%	0.06%	0.03%	0.07%	0.00%	1.61%
20	0.66%	0.01%	0.02%	0.01%	0.18%	0.57%	0.21%	0.08%	0.07%	0.16%	0.04%	0.08%	0.00%	2.08%
21	0.86%	0.00%	0.00%	0.00%	0.11%	0.81%	0.28%	0.13%	0.01%	0.01%	0.03%	0.07%	0.06%	2.37%
22	1.73%	0.27%	0.09%	0.03%	0.19%	0.00%	0.21%	0.03%	0.13%	0.33%	0.05%	0.07%	0.00%	3.12%
23	1.84%	0.35%	0.12%	0.03%	0.21%	0.02%	0.18%	0.03%	0.18%	0.45%	0.06%	0.07%	0.00%	3.55%
24	0.39%	0.12%	0.03%	0.02%	0.16%	0.21%	0.32%	0.10%	0.01%	0.06%	0.03%	0.05%	0.00%	1.49%
25	1.86%	0.27%	0.09%	0.04%	0.20%	0.26%	0.11%	0.00%	0.14%	0.32%	0.05%	0.08%	0.00%	3.41%
26	1.98%	0.35%	0.12%	0.04%	0.23%	0.25%	0.07%	0.00%	0.19%	0.45%	0.06%	0.08%	0.00%	3.83%
27	0.56%	0.12%	0.03%	0.03%	0.17%	0.57%	0.14%	0.08%	0.02%	0.05%	0.03%	0.06%	0.00%	1.86%
28	0.79%	0.01%	0.02%	0.04%	0.19%	0.64%	0.14%	0.08%	0.06%	0.15%	0.04%	0.07%	0.00%	2.23%
29	1.02%	0.00%	0.00%	0.02%	0.13%	0.89%	0.18%	0.13%	0.00%	0.00%	0.03%	0.06%	0.06%	2.53%
30	1.86%	0.27%	0.09%	0.04%	0.20%	0.06%	0.18%	0.03%	0.12%	0.32%	0.05%	0.06%	0.00%	3.28%
31	1.97%	0.35%	0.12%	0.05%	0.22%	0.07%	0.11%	0.03%	0.18%	0.45%	0.06%	0.07%	0.00%	3.67%
32	0.60%	0.12%	0.03%	0.04%	0.17%	0.29%	0.21%	0.10%	0.00%	0.05%	0.03%	0.04%	0.00%	1.68%
33	1.86%	0.27%	0.09%	0.05%	0.22%	0.01%	0.07%	0.00%	0.14%	0.33%	0.05%	0.09%	0.00%	3.18%
34	2.00%	0.35%	0.12%	0.05%	0.24%	0.02%	0.04%	0.00%	0.19%	0.46%	0.06%	0.09%	0.00%	3.62%
35	0.60%	0.12%	0.03%	0.05%	0.18%	0.21%	0.14%	0.08%	0.03%	0.07%	0.03%	0.07%	0.00%	1.62%
36	0.81%	0.01%	0.02%	0.05%	0.20%	0.32%	0.11%	0.08%	0.07%	0.16%	0.04%	0.08%	0.00%	1.96%
37	1.01%	0.00%	0.00%	0.04%	0.15%	0.48%	0.11%	0.13%	0.01%	0.02%	0.03%	0.08%	0.06%	2.13%
Sum	43.03%	6.69%	2.23%	1.23%	6.17%	18.22%	4.70%	2.02%	3.38%	8.34%	1.37%	2.24%	0.37%	100.00%

Annexure 68: Normalised, weighted scores for BPA III

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria					Sum
	IRR (30 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (30 yrs)	OPEX (30 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	1.69%	0.27%	0.09%	0.03%	0.19%	0.24%	0.07%	0.00%	0.14%	0.33%	0.04%	0.02%	0.01%	3.14%
2	1.73%	0.35%	0.12%	0.04%	0.22%	0.23%	0.07%	0.00%	0.19%	0.45%	0.05%	0.02%	0.01%	3.48%
3	0.44%	0.12%	0.03%	0.01%	0.16%	0.56%	0.11%	0.08%	0.03%	0.07%	0.04%	0.02%	0.01%	1.66%
4	0.84%	0.01%	0.02%	0.02%	0.18%	0.60%	0.11%	0.08%	0.07%	0.16%	0.04%	0.02%	0.01%	2.16%
5	1.01%	0.00%	0.00%	0.01%	0.12%	0.88%	0.14%	0.13%	0.01%	0.02%	0.03%	0.37%	0.01%	2.72%
6	1.72%	0.27%	0.09%	0.04%	0.20%	0.05%	0.14%	0.03%	0.13%	0.33%	0.04%	0.02%	0.01%	3.06%
7	1.75%	0.35%	0.12%	0.04%	0.22%	0.06%	0.11%	0.03%	0.18%	0.45%	0.04%	0.02%	0.01%	3.38%
8	0.51%	0.12%	0.03%	0.02%	0.16%	0.30%	0.22%	0.10%	0.01%	0.07%	0.03%	0.02%	0.01%	1.59%
9	1.33%	0.27%	0.09%	0.04%	0.11%	0.90%	0.00%	0.00%	0.13%	0.32%	0.03%	0.01%	0.01%	3.24%
10	1.32%	0.35%	0.12%	0.04%	0.15%	0.79%	0.00%	0.00%	0.19%	0.44%	0.03%	0.02%	0.01%	3.46%
11	0.00%	0.12%	0.03%	0.03%	0.06%	1.49%	0.04%	0.08%	0.02%	0.05%	0.01%	0.01%	0.00%	1.94%
12	0.58%	0.01%	0.02%	0.04%	0.09%	1.40%	0.00%	0.08%	0.06%	0.15%	0.02%	0.01%	0.00%	2.45%
13	0.72%	0.00%	0.00%	0.02%	0.00%	1.93%	0.04%	0.13%	0.00%	0.00%	0.00%	0.36%	0.00%	3.20%
14	1.41%	0.27%	0.09%	0.04%	0.14%	0.68%	0.07%	0.03%	0.12%	0.32%	0.02%	0.02%	0.01%	3.20%
15	1.40%	0.35%	0.12%	0.05%	0.17%	0.59%	0.04%	0.03%	0.17%	0.44%	0.03%	0.02%	0.01%	3.41%
16	0.19%	0.12%	0.03%	0.04%	0.09%	1.18%	0.11%	0.10%	0.00%	0.05%	0.00%	0.01%	0.00%	1.91%
17	1.67%	0.27%	0.09%	0.03%	0.19%	0.18%	0.18%	0.00%	0.14%	0.33%	0.05%	0.01%	0.01%	3.14%
18	1.69%	0.35%	0.12%	0.03%	0.22%	0.18%	0.14%	0.00%	0.19%	0.45%	0.05%	0.01%	0.02%	3.45%
19	0.38%	0.12%	0.03%	0.01%	0.16%	0.48%	0.25%	0.08%	0.03%	0.06%	0.04%	0.00%	0.01%	1.65%
20	0.82%	0.01%	0.02%	0.01%	0.17%	0.53%	0.22%	0.08%	0.07%	0.16%	0.05%	0.01%	0.01%	2.15%
21	0.98%	0.00%	0.00%	0.00%	0.11%	0.79%	0.29%	0.13%	0.01%	0.01%	0.04%	0.35%	0.01%	2.73%
22	1.69%	0.27%	0.09%	0.03%	0.20%	0.00%	0.25%	0.03%	0.13%	0.33%	0.04%	0.01%	0.01%	3.08%
23	1.71%	0.35%	0.12%	0.03%	0.22%	0.01%	0.18%	0.03%	0.18%	0.45%	0.05%	0.02%	0.02%	3.36%
24	0.46%	0.12%	0.03%	0.02%	0.16%	0.22%	0.33%	0.10%	0.01%	0.06%	0.03%	0.01%	0.01%	1.55%
25	1.78%	0.27%	0.09%	0.04%	0.20%	0.24%	0.11%	0.00%	0.14%	0.32%	0.05%	0.01%	0.01%	3.25%
26	1.80%	0.35%	0.12%	0.04%	0.22%	0.23%	0.11%	0.00%	0.19%	0.45%	0.05%	0.01%	0.02%	3.58%
27	0.64%	0.12%	0.03%	0.03%	0.17%	0.56%	0.14%	0.08%	0.02%	0.05%	0.04%	0.00%	0.01%	1.89%
28	0.94%	0.01%	0.02%	0.04%	0.18%	0.60%	0.11%	0.08%	0.06%	0.15%	0.04%	0.01%	0.01%	2.25%
29	1.14%	0.00%	0.00%	0.02%	0.13%	0.88%	0.18%	0.13%	0.01%	0.00%	0.04%	0.35%	0.01%	2.88%
30	1.80%	0.27%	0.13%	0.04%	0.21%	0.05%	0.18%	0.03%	0.12%	0.32%	0.04%	0.01%	0.01%	3.22%
31	1.82%	0.35%	0.12%	0.05%	0.23%	0.06%	0.14%	0.03%	0.18%	0.45%	0.04%	0.01%	0.02%	3.49%
32	0.67%	0.12%	0.03%	0.04%	0.17%	0.30%	0.25%	0.10%	0.00%	0.05%	0.03%	0.00%	0.01%	1.78%
33	1.78%	0.27%	0.09%	0.05%	0.21%	0.00%	0.04%	0.00%	0.14%	0.33%	0.05%	0.02%	0.01%	3.01%
34	1.82%	0.35%	0.12%	0.06%	0.23%	0.02%	0.04%	0.00%	0.19%	0.46%	0.05%	0.02%	0.02%	3.38%
35	0.69%	0.12%	0.03%	0.05%	0.18%	0.23%	0.11%	0.08%	0.03%	0.07%	0.05%	0.02%	0.01%	1.66%
36	0.96%	0.01%	0.02%	0.05%	0.20%	0.31%	0.07%	0.08%	0.07%	0.16%	0.05%	0.02%	0.01%	2.02%
37	1.13%	0.00%	0.00%	0.04%	0.14%	0.49%	0.11%	0.13%	0.01%	0.02%	0.05%	0.37%	0.01%	2.51%
Sum	43.03%	6.69%	2.23%	1.23%	6.17%	18.22%	4.70%	2.02%	3.38%	8.34%	1.37%	2.24%	0.37%	100.00%

Annexure 69: Normalised, weighted scores for BPA IV

LBS	Financial-economic criteria					Socio-economic criteria			Environmental impact criteria					Sum
	IRR (35 years)	Cost of Conversion technology		Cost other than conversion technology		Direct Employment Creation Potential			Local Impact			Global Impact		
		CAPEX (20 yrs)	OPEX (20 yrs)	CAPEX (35 yrs)	OPEX (35 yrs)	DECP I	DECP II	DECP III	AP	EP	POCP	ADP fossil	GWP 100 years	
1	1.73%	0.27%	0.09%	0.03%	0.19%	0.24%	0.08%	0.00%	0.14%	0.33%	0.05%	0.01%	0.01%	3.17%
2	1.74%	0.35%	0.12%	0.04%	0.22%	0.23%	0.08%	0.00%	0.19%	0.45%	0.05%	0.02%	0.02%	3.50%
3	0.38%	0.12%	0.03%	0.01%	0.16%	0.58%	0.15%	0.08%	0.03%	0.06%	0.03%	0.01%	0.01%	1.65%
4	0.85%	0.01%	0.02%	0.02%	0.18%	0.62%	0.11%	0.08%	0.07%	0.16%	0.04%	0.01%	0.01%	2.18%
5	1.03%	0.00%	0.00%	0.01%	0.12%	0.91%	0.15%	0.13%	0.01%	0.02%	0.03%	0.38%	0.01%	2.79%
6	1.74%	0.27%	0.09%	0.03%	0.20%	0.05%	0.15%	0.03%	0.13%	0.33%	0.04%	0.02%	0.01%	3.08%
7	1.76%	0.35%	0.12%	0.04%	0.22%	0.06%	0.11%	0.03%	0.18%	0.45%	0.04%	0.02%	0.01%	3.40%
8	0.48%	0.12%	0.03%	0.02%	0.17%	0.30%	0.23%	0.10%	0.01%	0.06%	0.02%	0.01%	0.01%	1.55%
9	1.35%	0.27%	0.09%	0.04%	0.12%	0.85%	0.00%	0.00%	0.14%	0.32%	0.03%	0.01%	0.01%	3.22%
10	1.32%	0.35%	0.12%	0.05%	0.15%	0.75%	0.00%	0.00%	0.19%	0.45%	0.03%	0.01%	0.01%	3.43%
11	0.00%	0.12%	0.03%	0.04%	0.06%	1.44%	0.04%	0.08%	0.02%	0.05%	0.01%	0.00%	0.00%	1.89%
12	0.55%	0.01%	0.02%	0.04%	0.09%	1.37%	0.04%	0.08%	0.06%	0.15%	0.02%	0.01%	0.00%	2.44%
13	0.70%	0.00%	0.00%	0.03%	0.00%	1.88%	0.04%	0.13%	0.00%	0.00%	0.01%	0.38%	0.00%	3.16%
14	1.42%	0.27%	0.09%	0.05%	0.14%	0.62%	0.08%	0.03%	0.12%	0.32%	0.02%	0.01%	0.01%	3.16%
15	1.39%	0.35%	0.12%	0.05%	0.17%	0.55%	0.04%	0.03%	0.18%	0.44%	0.03%	0.01%	0.01%	3.36%
16	0.17%	0.12%	0.03%	0.04%	0.09%	1.12%	0.11%	0.10%	0.00%	0.05%	0.00%	0.01%	0.00%	1.84%
17	1.71%	0.27%	0.09%	0.02%	0.19%	0.20%	0.15%	0.00%	0.14%	0.33%	0.05%	0.01%	0.01%	3.17%
18	1.72%	0.35%	0.12%	0.03%	0.22%	0.19%	0.15%	0.00%	0.19%	0.45%	0.05%	0.01%	0.02%	3.50%
19	0.32%	0.12%	0.03%	0.00%	0.15%	0.51%	0.26%	0.08%	0.03%	0.06%	0.04%	0.00%	0.01%	1.62%
20	0.82%	0.01%	0.02%	0.01%	0.18%	0.56%	0.19%	0.08%	0.07%	0.16%	0.05%	0.01%	0.01%	2.14%
21	1.00%	0.00%	0.00%	0.00%	0.12%	0.83%	0.30%	0.13%	0.01%	0.01%	0.04%	0.38%	0.01%	2.82%
22	1.72%	0.27%	0.09%	0.03%	0.19%	0.00%	0.23%	0.03%	0.13%	0.33%	0.04%	0.01%	0.01%	3.08%
23	1.74%	0.35%	0.12%	0.03%	0.22%	0.01%	0.19%	0.03%	0.18%	0.45%	0.05%	0.01%	0.02%	3.40%
24	0.43%	0.12%	0.03%	0.01%	0.16%	0.23%	0.34%	0.10%	0.01%	0.06%	0.03%	0.01%	0.01%	1.54%
25	1.80%	0.27%	0.09%	0.04%	0.20%	0.25%	0.08%	0.00%	0.14%	0.32%	0.05%	0.01%	0.01%	3.25%
26	1.81%	0.35%	0.12%	0.04%	0.23%	0.23%	0.08%	0.00%	0.19%	0.45%	0.05%	0.01%	0.02%	3.57%
27	0.57%	0.12%	0.03%	0.03%	0.16%	0.59%	0.15%	0.08%	0.02%	0.05%	0.04%	0.00%	0.01%	1.85%
28	0.94%	0.01%	0.02%	0.04%	0.19%	0.62%	0.11%	0.08%	0.06%	0.15%	0.04%	0.00%	0.01%	2.27%
29	1.15%	0.00%	0.00%	0.03%	0.13%	0.91%	0.19%	0.13%	0.00%	0.00%	0.03%	0.37%	0.01%	2.96%
30	1.82%	0.27%	0.09%	0.04%	0.20%	0.05%	0.15%	0.03%	0.12%	0.32%	0.04%	0.01%	0.01%	3.16%
31	1.83%	0.35%	0.12%	0.05%	0.23%	0.06%	0.11%	0.03%	0.18%	0.45%	0.04%	0.01%	0.02%	3.47%
32	0.63%	0.12%	0.03%	0.04%	0.17%	0.30%	0.23%	0.10%	0.00%	0.05%	0.03%	0.00%	0.01%	1.71%
33	1.82%	0.27%	0.09%	0.05%	0.21%	0.00%	0.04%	0.00%	0.14%	0.33%	0.05%	0.02%	0.01%	3.04%
34	1.83%	0.35%	0.12%	0.06%	0.23%	0.02%	0.04%	0.00%	0.19%	0.46%	0.06%	0.02%	0.02%	3.39%
35	0.63%	0.12%	0.03%	0.05%	0.18%	0.24%	0.15%	0.08%	0.03%	0.07%	0.05%	0.01%	0.01%	1.65%
36	0.97%	0.01%	0.02%	0.05%	0.20%	0.32%	0.08%	0.08%	0.07%	0.16%	0.05%	0.02%	0.01%	2.04%
37	1.15%	0.00%	0.00%	0.05%	0.14%	0.51%	0.11%	0.13%	0.01%	0.02%	0.05%	0.39%	0.01%	2.57%
Sum	43.03%	6.69%	2.23%	1.23%	6.17%	18.22%	4.70%	2.02%	3.38%	8.34%	1.37%	2.24%	0.37%	100.00%

Annexure 70: Comparison of the top-ten ranked LBSs across all four BPAs

Paarl biomass procurement area						
Ranking	LBS[1]	relative weight of main criteria			BCS[5]	HS[6]
		Fin.-Econ.[2]	Soc.-econ.[3]	Environ.[4]		
1	26	75	8	18	2	4
2	31	76	7	17	2	4
3	2	74	8	19	2	1
4	7	75	7	18	2	1
5	34	79	2	19	2	5
6	18	73	8	19	2	3
7	23	74	8	18	2	3
8	15	62	20	18	2	2
9	25	77	8	15	1	4
10	30	78	8	14	1	4
	average:	74.3	8.4	17.5	1.8	3.1
	median:	75	8	18	2	3.5

Worcester biomass procurement area						
Ranking	LBS[2]	relative weight of main criteria			BCS[5]	HS[6]
		Fin.-Econ.[2]	Soc.-econ.[3]	Environ.[4]		
1	26	73	9	19	2	4
2	2	72	9	19	2	1
3	18	71	9	20	2	3
4	31	76	6	19	2	4
5	10	60	22	19	2	2
6	34	78	2	20	2	5
7	7	75	6	20	2	1
8	23	74	7	20	2	3
9	15	64	18	18	2	2
10	25	74	11	15	1	4
	average:	71.7	9.9	18.9	1.9	2.9
	median:	73.5	9	19	2	3

Ashton biomass procurement area						
Ranking	LBS[1]	relative weight of main criteria			BCS[5]	HS[6]
		Fin.-Econ.[2]	Soc.-econ.[3]	Environ.[4]		
1	13	21	58	21	5	2
2	26	72	10	18	2	4
3	31	75	7	18	2	4
4	2	72	9	19	2	1
5	10	59	23	18	2	2
6	18	71	9	19	2	3
7	15	62	20	18	2	2
8	7	75	6	19	2	1
9	34	78	2	20	2	5
10	23	74	7	19	2	3
	average:	65.9	15.1	18.9	2.3	2.7
	median:	72	9	19	2	2.5

Rural Cederberge biomass procurement area						
Ranking	LBS[2]	relative weight of main criteria			BCS[5]	HS[6]
		Fin.-Econ.[2]	Soc.-econ.[3]	Environ.[4]		
1	13	21	57	22	5	2
2	26	73	9	18	2	4
3	18	71	10	19	2	3
4	2	72	9	19	2	1
5	31	76	6	18	2	4
6	29	39	37	25	5	4
7	10	59	22	18	2	2
8	7	75	6	19	2	1
9	23	74	7	19	2	3
10	34	78	2	20	2	5
	average:	63.8	16.5	19.7	2.6	2.9
	median:	72.5	9	19	2	3

Notes:

[1] Lignocellulosic bioenergy system
[2] Financial-economic viability
[3] Socio-economic potential
[4] Least environmental impact
[5] Bioenergy conversion system
[6] Harvesting system

Annexure 71: Maximisation of financial-economic main criterion

LBS	Biomass procurement areas			
	Paarl	Worcester	Ashton	R. Cederberge
1	4.333%	3.934%	3.833%	3.891%
2	4.727%	4.394%	4.130%	4.159%
3	0.523%	1.124%	1.278%	1.163%
4	1.415%	1.554%	1.803%	1.804%
5	1.720%	1.713%	1.916%	1.944%
6	4.368%	3.958%	3.893%	3.927%
7	4.773%	4.377%	4.172%	4.204%
8	0.668%	1.305%	1.428%	1.366%
9	3.210%	3.213%	3.101%	3.140%
10	3.479%	3.568%	3.343%	3.353%
11	0.362%	0.403%	0.406%	0.421%
12	0.638%	1.066%	1.225%	1.204%
13	0.804%	1.125%	1.245%	1.238%
14	3.441%	3.370%	3.282%	3.298%
15	3.720%	3.701%	3.508%	3.490%
16	0.433%	0.792%	0.778%	0.771%
17	4.259%	3.859%	3.773%	3.843%
18	4.642%	4.323%	4.060%	4.104%
19	0.508%	1.014%	1.173%	1.057%
20	1.348%	1.489%	1.739%	1.736%
21	1.644%	1.640%	1.849%	1.883%
22	4.298%	3.884%	3.833%	3.880%
23	4.685%	4.306%	4.103%	4.150%
24	0.537%	1.202%	1.329%	1.266%
25	4.564%	4.141%	3.999%	4.040%
26	4.952%	4.590%	4.272%	4.297%
27	0.909%	1.525%	1.661%	1.542%
28	1.672%	1.763%	2.002%	2.002%
29	2.038%	1.979%	2.172%	2.203%
30	4.602%	4.143%	4.128%	4.077%
31	4.998%	4.574%	4.314%	4.342%
32	1.029%	1.609%	1.736%	1.663%
33	4.646%	4.187%	4.054%	4.108%
34	5.052%	4.649%	4.349%	4.370%
35	1.111%	1.650%	1.801%	1.699%
36	1.782%	1.848%	2.090%	2.107%
37	2.108%	2.029%	2.221%	2.259%
sum	100.000%	100.000%	100.000%	100.000%
max	0.362%	0.403%	0.406%	0.421%
average	5.052%	4.649%	4.349%	4.370%

Annexure 72: Maximisation of socio-economic main criterion

LBSs	Biomass procurement areas			
	Paarl	Worcester	Ashton	R. Cederberge
1	1.135%	1.315%	1.259%	1.276%
2	1.163%	1.267%	1.193%	1.207%
3	2.994%	3.176%	2.989%	3.254%
4	3.229%	3.439%	3.165%	3.266%
5	4.638%	4.673%	4.616%	4.759%
6	1.100%	0.889%	0.902%	0.914%
7	1.086%	0.818%	0.780%	0.787%
8	2.779%	2.391%	2.469%	2.521%
9	3.322%	3.470%	3.590%	3.412%
10	3.018%	3.087%	3.150%	2.994%
11	6.080%	6.218%	6.444%	6.237%
12	5.817%	5.979%	5.924%	5.936%
13	8.168%	8.170%	8.389%	8.206%
14	3.149%	2.925%	3.102%	2.911%
15	2.802%	2.519%	2.626%	2.458%
16	5.671%	5.266%	5.581%	5.342%
17	1.191%	1.361%	1.451%	1.392%
18	1.219%	1.361%	1.285%	1.346%
19	3.063%	3.293%	3.238%	3.405%
20	3.202%	3.437%	3.314%	3.312%
21	4.653%	4.885%	4.822%	5.037%
22	1.128%	0.959%	1.117%	1.007%
23	1.142%	0.912%	0.871%	0.902%
24	2.848%	2.532%	2.595%	2.695%
25	1.163%	1.457%	1.404%	1.299%
26	1.191%	1.291%	1.338%	1.230%
27	3.021%	3.176%	3.134%	3.278%
28	3.257%	3.439%	3.165%	3.266%
29	4.638%	4.816%	4.761%	4.933%
30	1.100%	1.055%	1.047%	0.914%
31	1.086%	0.818%	0.924%	0.787%
32	2.806%	2.415%	2.614%	2.521%
33	0.250%	0.309%	0.145%	0.151%
34	0.236%	0.238%	0.211%	0.220%
35	1.692%	1.740%	1.645%	1.885%
36	1.969%	2.028%	1.831%	1.909%
37	2.991%	2.879%	2.908%	3.030%
sum	100.000%	100.000%	100.000%	100.000%
max	0.236%	0.238%	0.145%	0.151%
average	8.168%	8.170%	8.389%	8.206%

Annexure 73: Maximisation of least environmental impact main criterion

LBS	Biomass procurement areas			
	Paarl	Worcester	Ashton	R. Cederberge
1	3.281%	3.286%	3.039%	3.012%
2	4.374%	4.360%	4.014%	3.993%
3	0.826%	0.864%	0.883%	0.827%
4	1.776%	1.760%	1.700%	1.662%
5	3.682%	3.626%	5.112%	5.249%
6	3.141%	3.155%	2.920%	2.880%
7	4.254%	4.247%	3.912%	3.879%
8	0.627%	0.678%	0.714%	0.640%
9	2.869%	2.833%	2.607%	2.612%
10	4.016%	3.970%	3.640%	3.657%
11	0.238%	0.221%	0.270%	0.264%
12	1.279%	1.212%	1.193%	1.186%
13	3.022%	2.903%	4.447%	4.621%
14	2.717%	2.692%	2.473%	2.462%
15	3.884%	3.849%	3.524%	3.528%
16	0.021%	0.021%	0.079%	0.051%
17	3.387%	3.399%	3.037%	3.034%
18	4.465%	4.457%	4.012%	4.011%
19	0.976%	1.024%	0.880%	0.858%
20	1.904%	1.898%	1.697%	1.688%
21	3.856%	3.810%	5.121%	5.283%
22	3.243%	3.265%	2.918%	2.901%
23	4.334%	4.339%	3.908%	3.900%
24	0.769%	0.834%	0.711%	0.674%
25	3.293%	3.309%	2.935%	2.925%
26	4.385%	4.379%	3.925%	3.918%
27	0.843%	0.896%	0.735%	0.703%
28	1.791%	1.788%	1.573%	1.556%
29	3.706%	3.665%	4.957%	5.109%
30	3.153%	3.177%	2.819%	2.796%
31	4.256%	4.264%	3.822%	3.809%
32	0.640%	0.709%	0.571%	0.524%
33	3.441%	3.477%	3.211%	3.175%
34	4.504%	4.523%	4.160%	4.135%
35	1.049%	1.135%	1.127%	1.062%
36	2.007%	2.012%	1.926%	1.880%
37	3.992%	3.961%	5.423%	5.537%
sum	100.000%	100.000%	100.000%	100.000%
min	2.189%	0.021%	0.079%	0.051%
max	3.085%	4.523%	5.423%	5.537%
average	2.703%	2.703%	2.703%	2.703%

Annexure 74: Ranking of LBSs based on maximised financial-economic criterion

Ranking	Biomass procurement area							
	Paarl		Worcester		Ashton		R. Cederberge	
	LBS	Weighted score	LBS	Weighted score	LBS	Weighted score	LBS	Weighted score
1	34	5.052%	34	4.649%	34	4.349%	34	4.370%
2	31	4.998%	26	4.590%	31	4.314%	31	4.342%
3	26	4.952%	31	4.574%	26	4.272%	26	4.297%
4	7	4.773%	2	4.394%	7	4.172%	7	4.204%
5	2	4.727%	7	4.377%	2	4.130%	2	4.159%
6	23	4.685%	18	4.323%	30	4.128%	23	4.150%
7	33	4.646%	23	4.306%	23	4.103%	33	4.108%
8	18	4.642%	33	4.187%	18	4.060%	18	4.104%
9	30	4.602%	30	4.143%	33	4.054%	30	4.077%
10	25	4.564%	25	4.141%	25	3.999%	25	4.040%
11	6	4.368%	6	3.958%	6	3.893%	6	3.927%
12	1	4.333%	1	3.934%	22	3.833%	1	3.891%
13	22	4.298%	22	3.884%	1	3.833%	22	3.880%
14	17	4.259%	17	3.859%	17	3.773%	17	3.843%
15	15	3.720%	15	3.701%	15	3.508%	15	3.490%
16	10	3.479%	10	3.568%	10	3.343%	10	3.353%
17	14	3.441%	14	3.370%	14	3.282%	14	3.298%
18	9	3.210%	9	3.213%	9	3.101%	9	3.140%
19	37	2.108%	37	2.029%	37	2.221%	37	2.259%
20	29	2.038%	29	1.979%	29	2.172%	29	2.203%
21	36	1.782%	36	1.848%	36	2.090%	36	2.107%
22	5	1.720%	28	1.763%	28	2.002%	28	2.002%
23	28	1.672%	5	1.713%	5	1.916%	5	1.944%
24	21	1.644%	35	1.650%	21	1.849%	21	1.883%
25	4	1.415%	21	1.640%	4	1.803%	4	1.804%
26	20	1.348%	32	1.609%	35	1.801%	20	1.736%
27	35	1.111%	4	1.554%	20	1.739%	35	1.699%
28	32	1.029%	27	1.525%	32	1.736%	32	1.663%
29	27	0.909%	20	1.489%	27	1.661%	27	1.542%
30	13	0.804%	8	1.305%	8	1.428%	8	1.366%
31	8	0.668%	24	1.202%	24	1.329%	24	1.266%
32	12	0.638%	13	1.125%	3	1.278%	13	1.238%
33	24	0.537%	3	1.124%	13	1.245%	12	1.204%
34	3	0.523%	12	1.066%	12	1.225%	3	1.163%
35	19	0.508%	19	1.014%	19	1.173%	19	1.057%
36	16	0.433%	16	0.792%	16	0.778%	16	0.771%
37	11	0.362%	11	0.403%	11	0.406%	11	0.421%

Annexure 75: Ranking of LBSs based on maximised socio-economic criterion

Ranking	Biomass procurement area							
	Paarl		Worcester		Ashton		R. Cederberge	
	LBS	Weighted score	LBS	Weighted score	LBS	Weighted score	LBS	Weighted score
1	13	8.168%	13	8.170%	13	8.389%	13	8.206%
2	11	6.080%	11	6.218%	11	6.444%	11	6.237%
3	12	5.817%	12	5.979%	12	5.924%	12	5.936%
4	16	5.671%	16	5.266%	16	5.581%	16	5.342%
5	21	4.653%	21	4.885%	21	4.822%	21	5.037%
6	5	4.638%	29	4.816%	29	4.761%	29	4.933%
7	29	4.638%	5	4.673%	5	4.616%	5	4.759%
8	9	3.322%	9	3.470%	9	3.590%	9	3.412%
9	28	3.257%	4	3.439%	20	3.314%	19	3.405%
10	4	3.229%	28	3.439%	19	3.238%	20	3.312%
11	20	3.202%	20	3.437%	4	3.165%	27	3.278%
12	14	3.149%	19	3.293%	28	3.165%	4	3.266%
13	19	3.063%	3	3.176%	10	3.150%	28	3.266%
14	27	3.021%	27	3.176%	27	3.134%	3	3.254%
15	10	3.018%	10	3.087%	14	3.102%	37	3.030%
16	3	2.994%	14	2.925%	3	2.989%	10	2.994%
17	37	2.991%	37	2.879%	37	2.908%	14	2.911%
18	24	2.848%	24	2.532%	15	2.626%	24	2.695%
19	32	2.806%	15	2.519%	32	2.614%	8	2.521%
20	15	2.802%	32	2.415%	24	2.595%	32	2.521%
21	8	2.779%	8	2.391%	8	2.469%	15	2.458%
22	36	1.969%	36	2.028%	36	1.831%	36	1.909%
23	35	1.692%	35	1.740%	35	1.645%	35	1.885%
24	18	1.219%	25	1.457%	17	1.451%	17	1.392%
25	17	1.191%	17	1.361%	25	1.404%	18	1.346%
26	26	1.191%	18	1.361%	26	1.338%	25	1.299%
27	2	1.163%	1	1.315%	18	1.285%	1	1.276%
28	25	1.163%	26	1.291%	1	1.259%	26	1.230%
29	23	1.142%	2	1.267%	2	1.193%	2	1.207%
30	1	1.135%	30	1.055%	22	1.117%	22	1.007%
31	22	1.128%	22	0.959%	30	1.047%	6	0.914%
32	6	1.100%	23	0.912%	31	0.924%	30	0.914%
33	30	1.100%	6	0.889%	6	0.902%	23	0.902%
34	7	1.086%	7	0.818%	23	0.871%	7	0.787%
35	31	1.086%	31	0.818%	7	0.780%	31	0.787%
36	33	0.250%	33	0.309%	34	0.211%	34	0.220%
37	34	0.236%	34	0.238%	33	0.145%	33	0.151%

Annexure 76: Ranking of LBSs based on maximised environmental impact criterion

Ranking	Biomass procurement area							
	Paarl		Worcester		Ashton		R. Cederberge	
	LBS	Weighted score	LBS	Weighted score	LBS	Weighted score	LBS	Weighted score
1	34	4.504%	34	4.523%	37	5.423%	37	5.537%
2	18	4.465%	18	4.457%	21	5.121%	21	5.283%
3	26	4.385%	26	4.379%	5	5.112%	5	5.249%
4	2	4.374%	2	4.360%	29	4.957%	29	5.109%
5	23	4.334%	23	4.339%	13	4.447%	13	4.621%
6	31	4.256%	31	4.264%	34	4.160%	34	4.135%
7	7	4.254%	7	4.247%	2	4.014%	18	4.011%
8	10	4.016%	10	3.970%	18	4.012%	2	3.993%
9	37	3.992%	37	3.961%	26	3.925%	26	3.918%
10	15	3.884%	15	3.849%	7	3.912%	23	3.900%
11	21	3.856%	21	3.810%	23	3.908%	7	3.879%
12	29	3.706%	29	3.665%	31	3.822%	31	3.809%
13	5	3.682%	5	3.626%	10	3.640%	10	3.657%
14	33	3.441%	33	3.477%	15	3.524%	15	3.528%
15	17	3.387%	17	3.399%	33	3.211%	33	3.175%
16	25	3.293%	25	3.309%	1	3.039%	17	3.034%
17	1	3.281%	1	3.286%	17	3.037%	1	3.012%
18	22	3.243%	22	3.265%	25	2.935%	25	2.925%
19	30	3.153%	30	3.177%	6	2.920%	22	2.901%
20	6	3.141%	6	3.155%	22	2.918%	6	2.880%
21	13	3.022%	13	2.903%	30	2.819%	30	2.796%
22	9	2.869%	9	2.833%	9	2.607%	9	2.612%
23	14	2.717%	14	2.692%	14	2.473%	14	2.462%
24	36	2.007%	36	2.012%	36	1.926%	36	1.880%
25	20	1.904%	20	1.898%	4	1.700%	20	1.688%
26	28	1.791%	28	1.788%	20	1.697%	4	1.662%
27	4	1.776%	4	1.760%	28	1.573%	28	1.556%
28	12	1.279%	12	1.212%	12	1.193%	12	1.186%
29	35	1.049%	35	1.135%	35	1.127%	35	1.062%
30	19	0.976%	19	1.024%	3	0.883%	19	0.858%
31	27	0.843%	27	0.896%	19	0.880%	3	0.827%
32	3	0.826%	3	0.864%	27	0.735%	27	0.703%
33	24	0.769%	24	0.834%	8	0.714%	24	0.674%
34	32	0.640%	32	0.709%	24	0.711%	8	0.640%
35	8	0.627%	8	0.678%	32	0.571%	32	0.524%
36	11	0.238%	11	0.221%	11	0.270%	11	0.264%
37	16	0.021%	16	0.021%	16	0.079%	16	0.051%